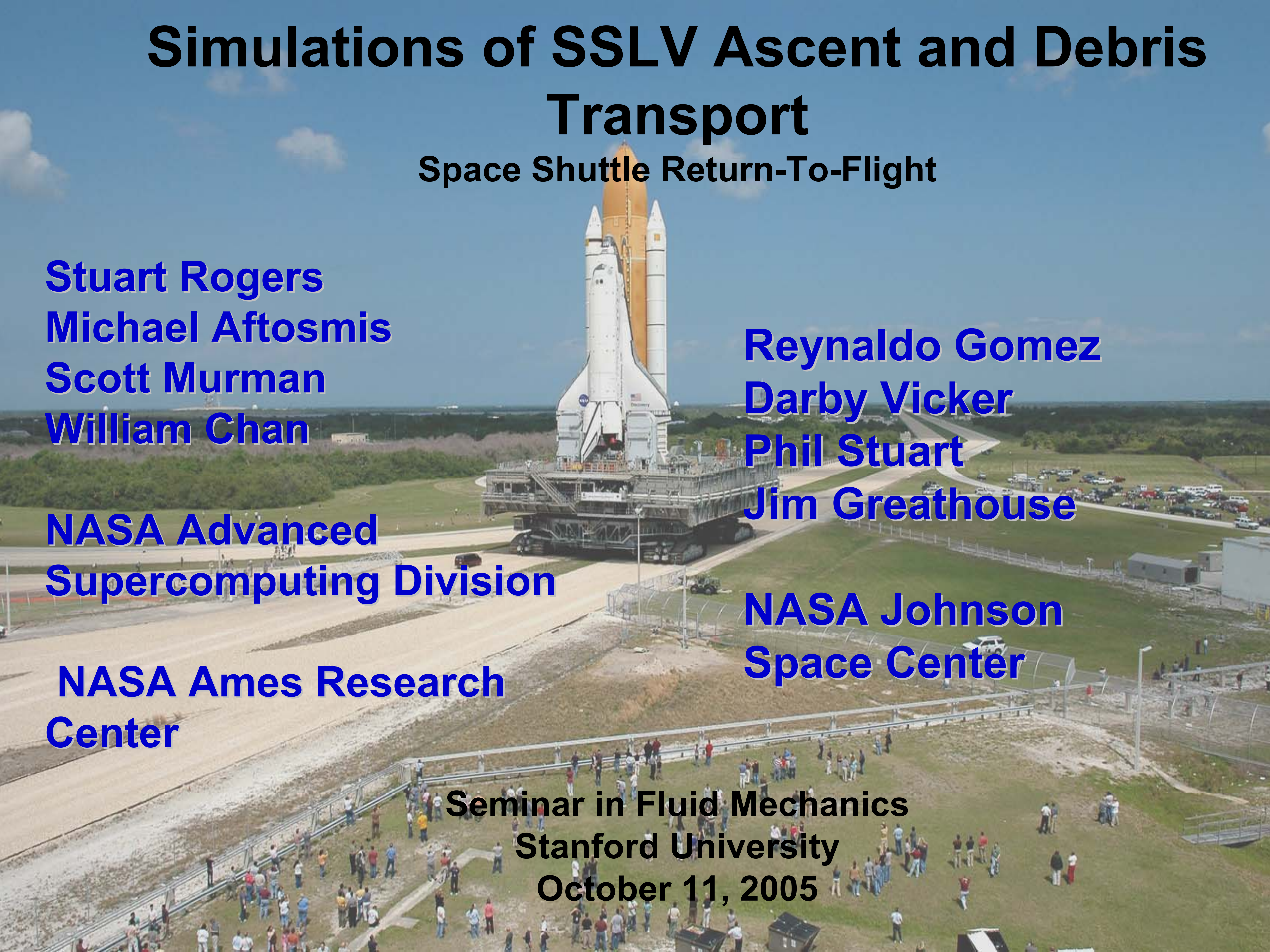

Simulations of SSLV Ascent and Debris Transport

Space Shuttle Return-To-Flight

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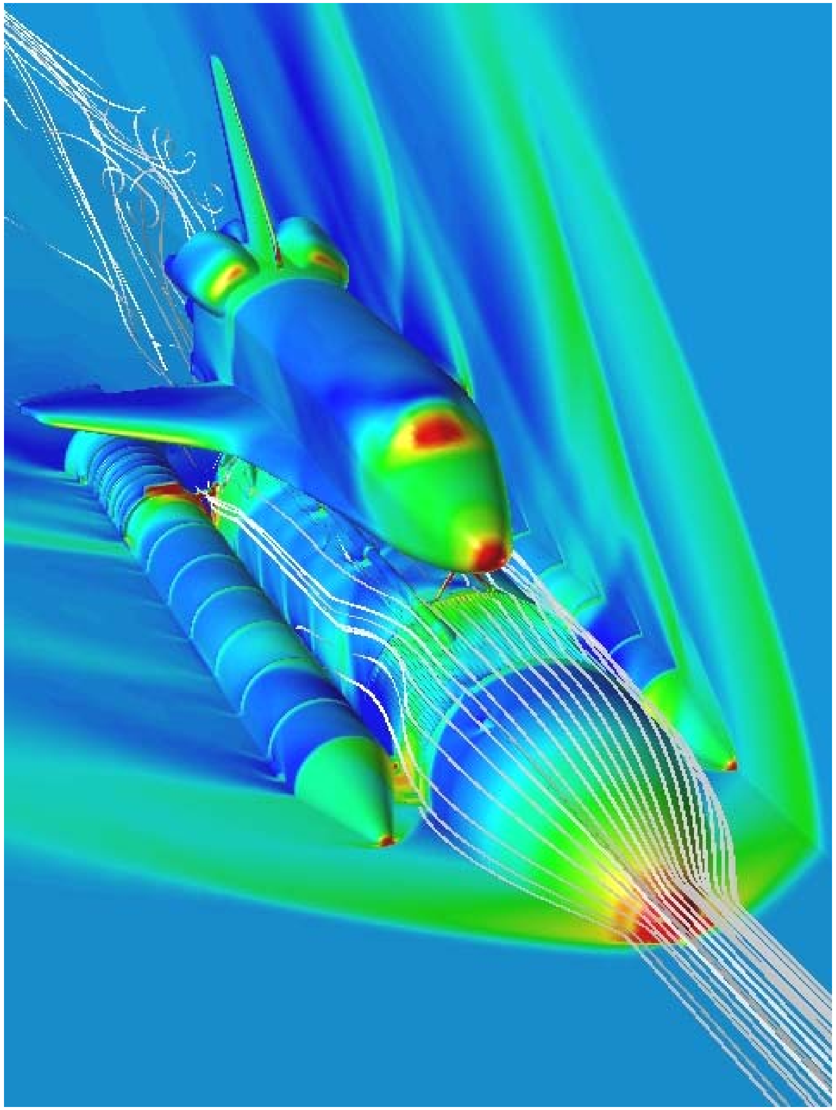
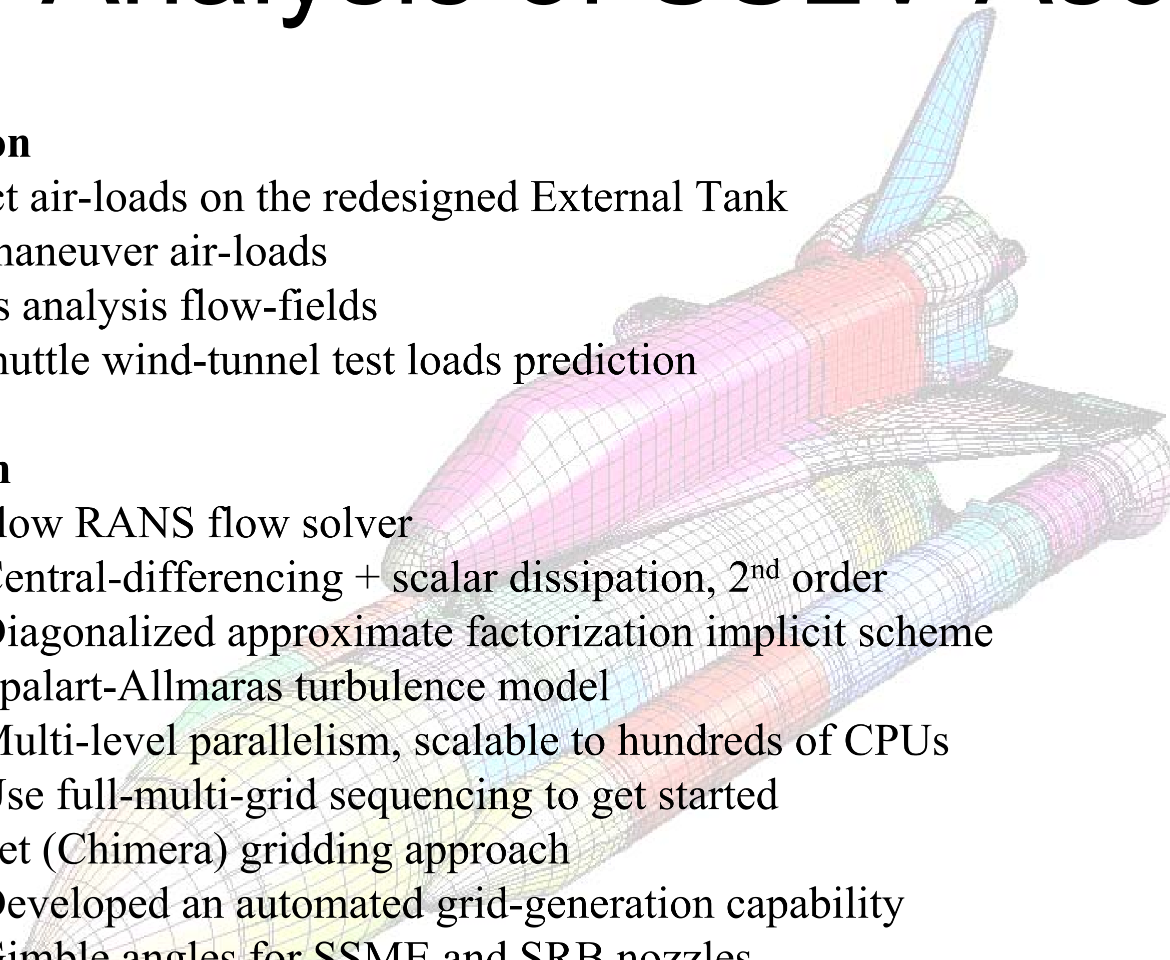
Seminar in Fluid Mechanics
Stanford University
October 11, 2005

Outline

- CFD simulations of the Space Shuttle Launch Vehicle ascent
- Debris transport analysis
- Debris aerodynamic modeling



CFD Analysis of SSLV Ascent



Motivation

- ❑ Predict air-loads on the redesigned External Tank
- ❑ Roll maneuver air-loads
- ❑ Debris analysis flow-fields
- ❑ 3% Shuttle wind-tunnel test loads prediction

Approach

- ❑ Overflow RANS flow solver
  - ➢ Central-differencing + scalar dissipation, 2nd order
  - ➢ Diagonalized approximate factorization implicit scheme
  - ➢ Spalart-Allmaras turbulence model
  - ➢ Multi-level parallelism, scalable to hundreds of CPUs
  - ➢ Use full-multi-grid sequencing to get started
- ❑ Overset (Chimera) gridding approach
  - ➢ Developed an automated grid-generation capability
  - ➢ Gimble angles for SSME and SRB nozzles
  - ➢ Control surface deflections
  - ➢ Plume boundary-condition generation for SSMEs and SRBs
- ❑ Validation with 3% WT model: Cp, PSP, PIV

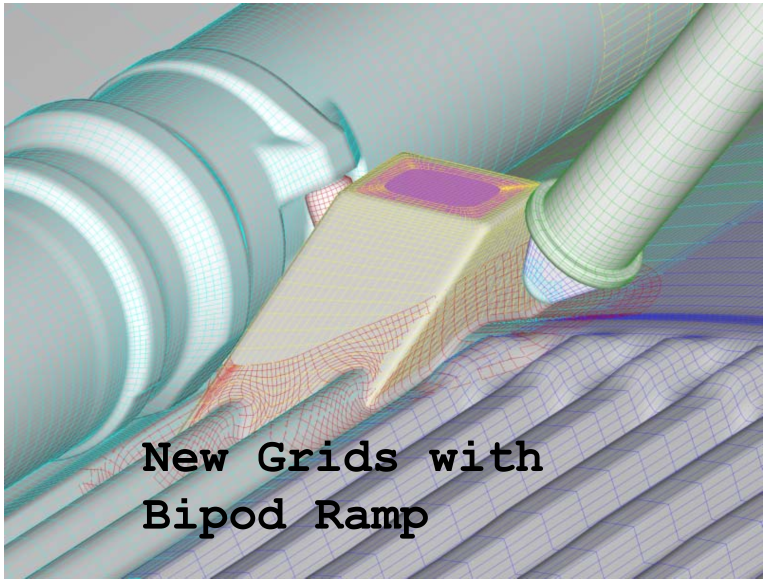
CFD Analysis of SSLV Ascent

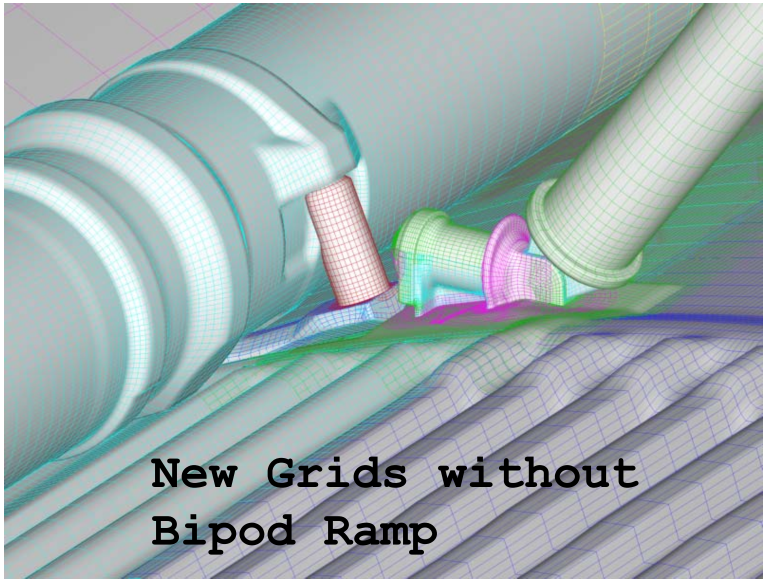
Results

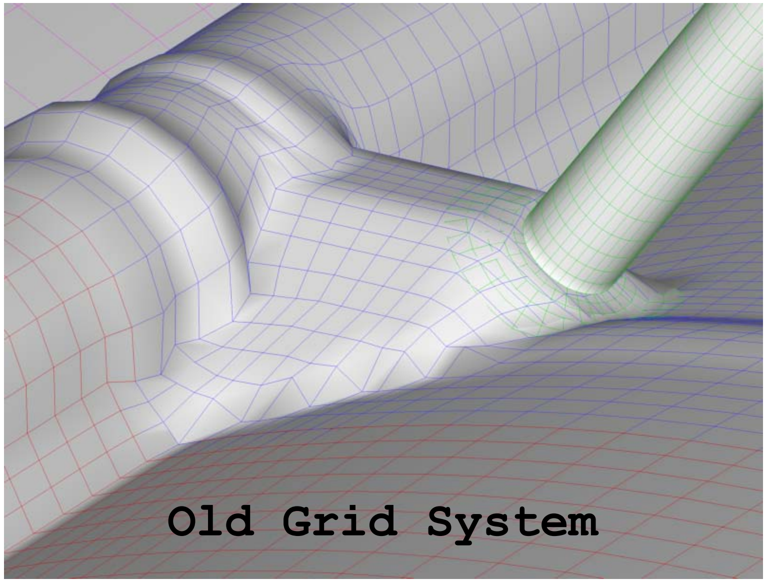
- Over 400 Overflow solutions run for Return-to-Flight
- New grids generated for each ascent condition
  - 2 hours on 32 Itanium-2 CPUs
  - 30 to 50 million grid points each

- Average of ~1000 Itanium-2 CPU hrs / solution
  - ~20 hours of wallclock time running on 64 Itanium-2 CPUs
  - Never converges to a steady-state: aft end of ET, attachment hardware, plumes, etc
  - Typically run for ~10,000 iterations

Geometry Details



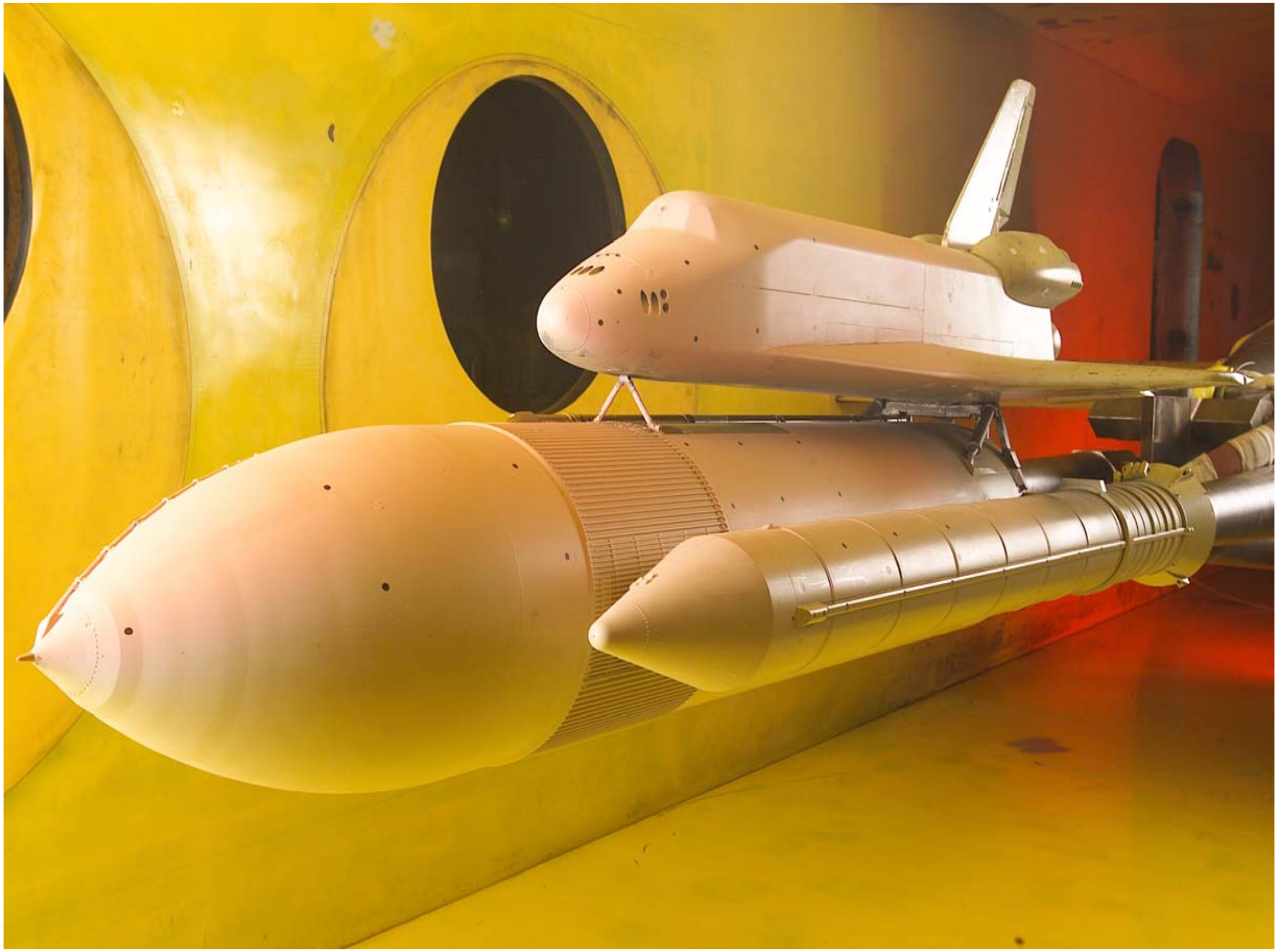




“Columbia”: World Class Supercomputing

- The NAS houses the world’s fastest operational supercomputer providing 61 teraflops of compute capability to the NASA user community
- Columbia is a 20-node supercomputer built on 512-processor nodes
- Columbia is the largest SGI system in the world with over 10,000 Intel Itanium2 processors

IA-700 Wind Tunnel Tests
ARC 9x7 Unitary, AEDC 16T



Wind Tunnel Test Comparisons - Orbiter Wing, Y = -380 inches

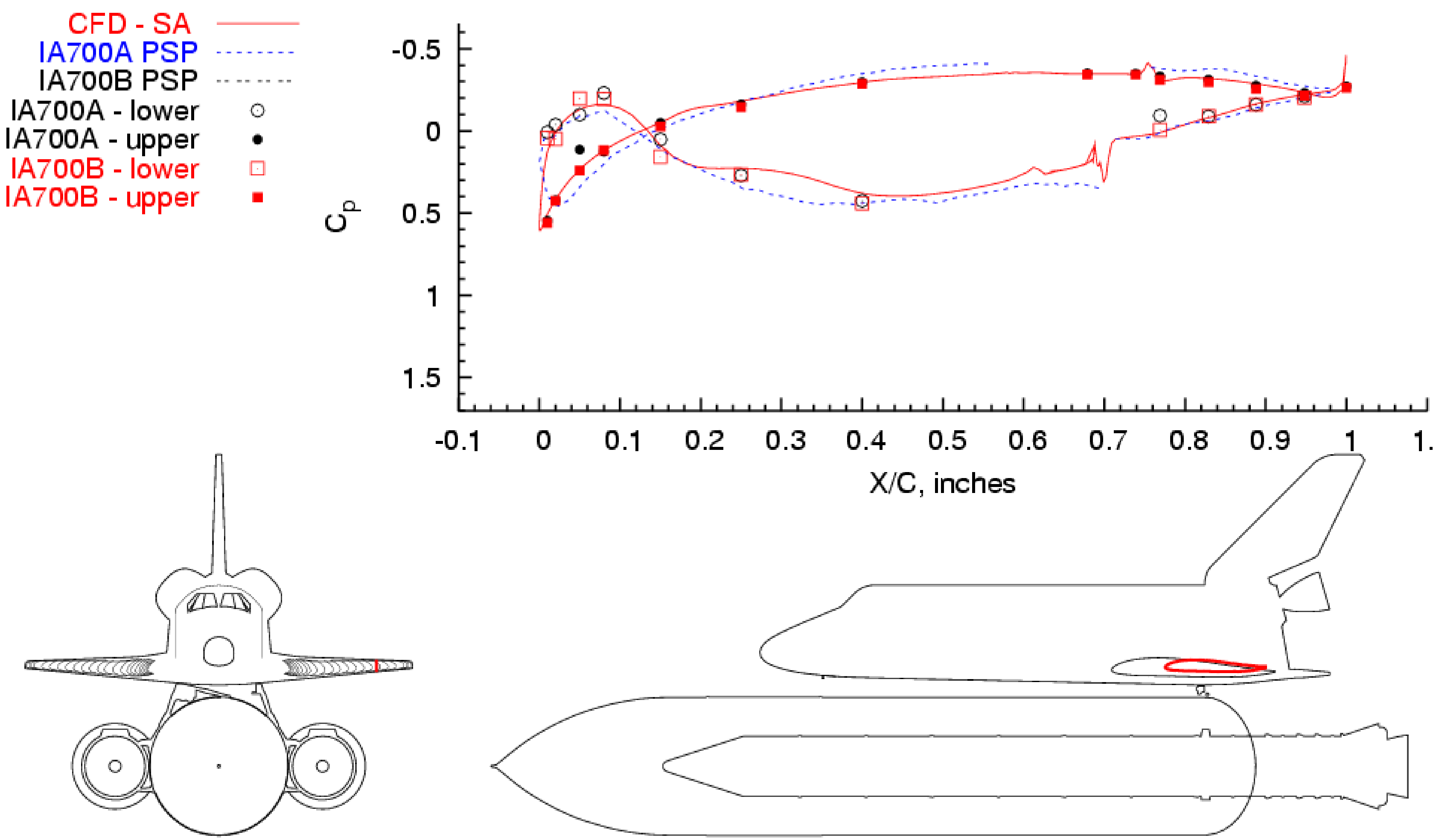
CFD - SA conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700A PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700B PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700A conditions: M_∞ = 1.550, α = 0.03°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 890, Point = 6, LOX Roll = 15°

IA700B conditions: M_∞ = 1.550, α = -0.33°, β = -0.27°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 212, Point = 4, LOX Roll = 0°



Wind Tunnel Test Comparisons - External Tank - Phi = 203.75°

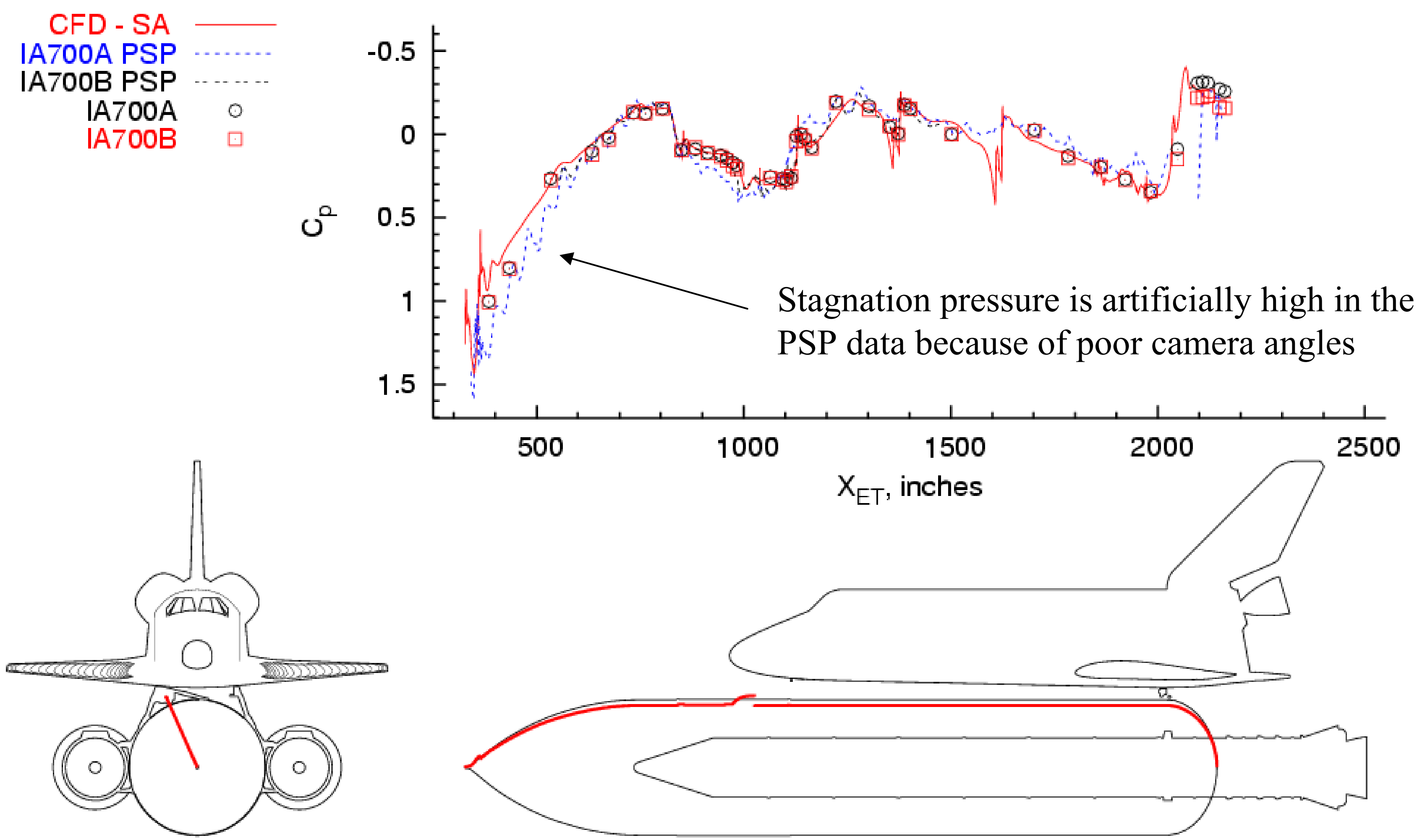
CFD - SA conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700A PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700B PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°

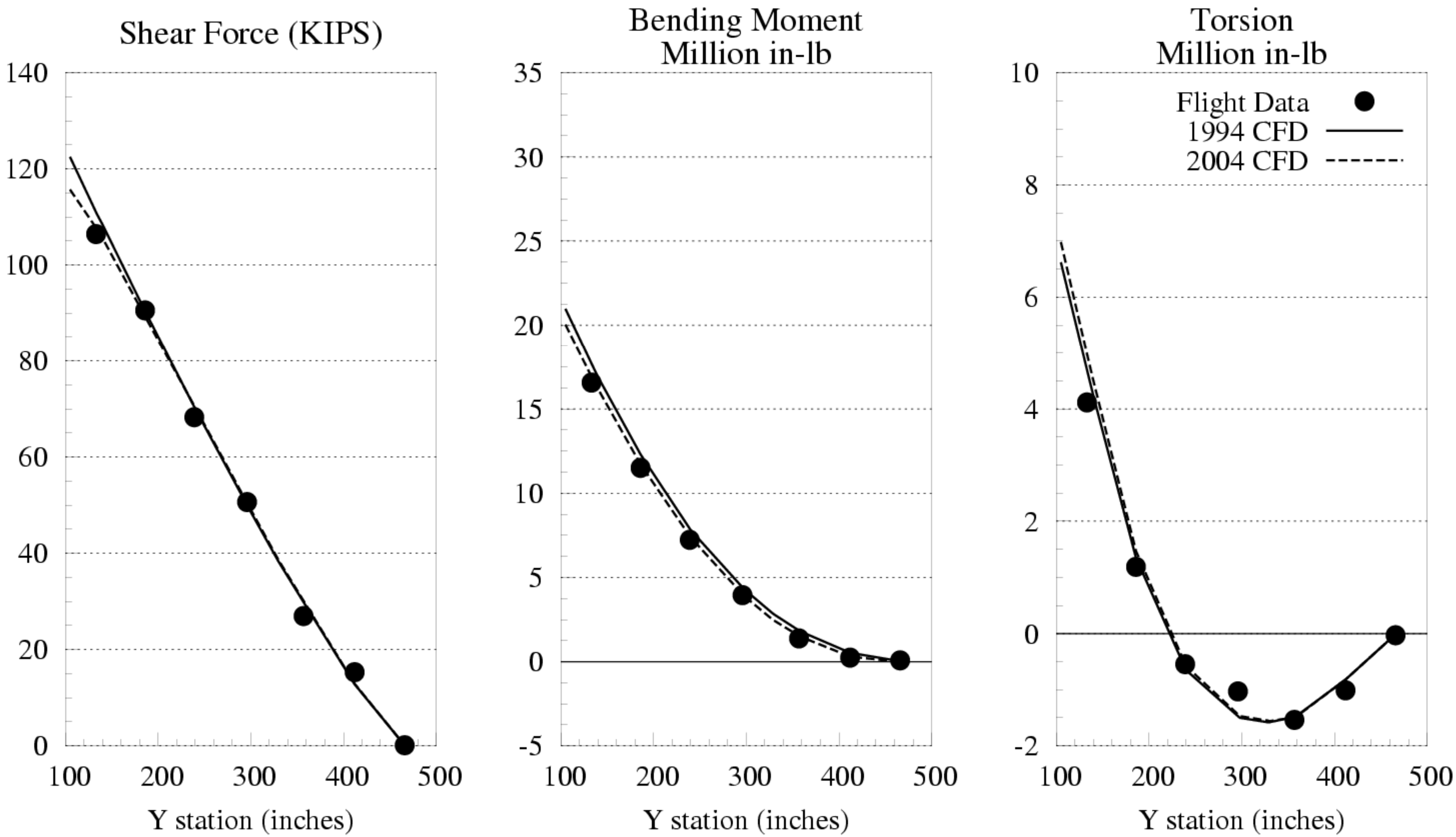
IA700A conditions: M_∞ = 1.550, α = 0.03°, β = 0.00°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 890, Point = 6, LOX Roll = 15°

IA700B conditions: M_∞ = 1.550, α = -0.33°, β = -0.27°, Reynolds # = 2.50 x10^6/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 212, Point = 4, LOX Roll = 0°



STS-50 Orbiter wing running loads

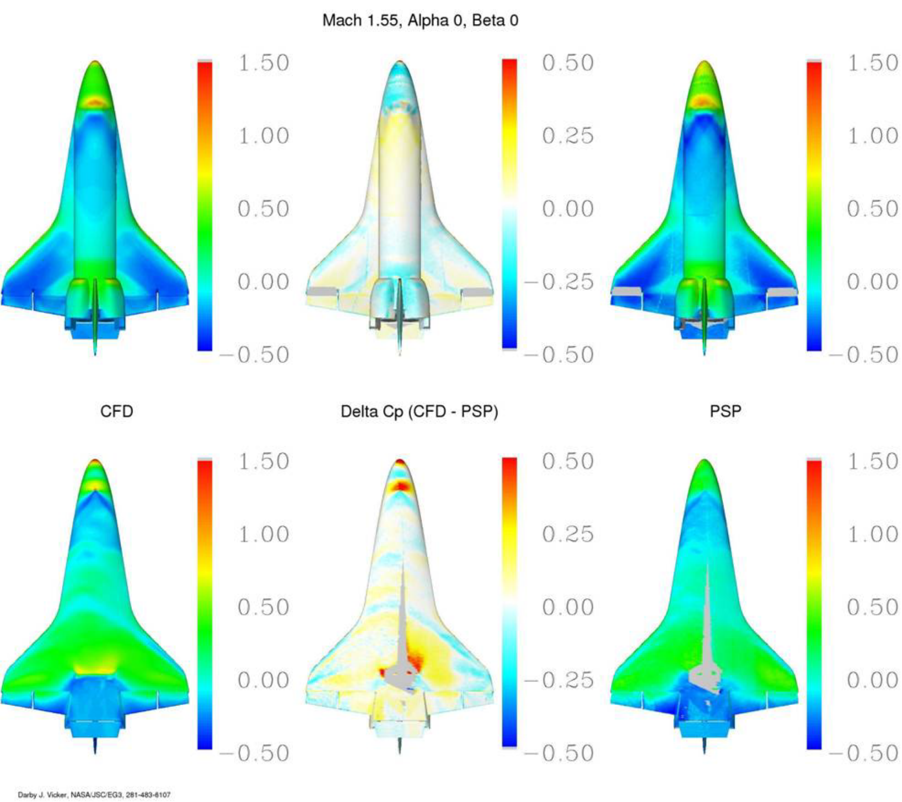
Mach 1.25, Alpha -3.3, Beta 0.0, $\delta_{ei/o}$ = 10.5/6.25, Qbar=640.7 psf

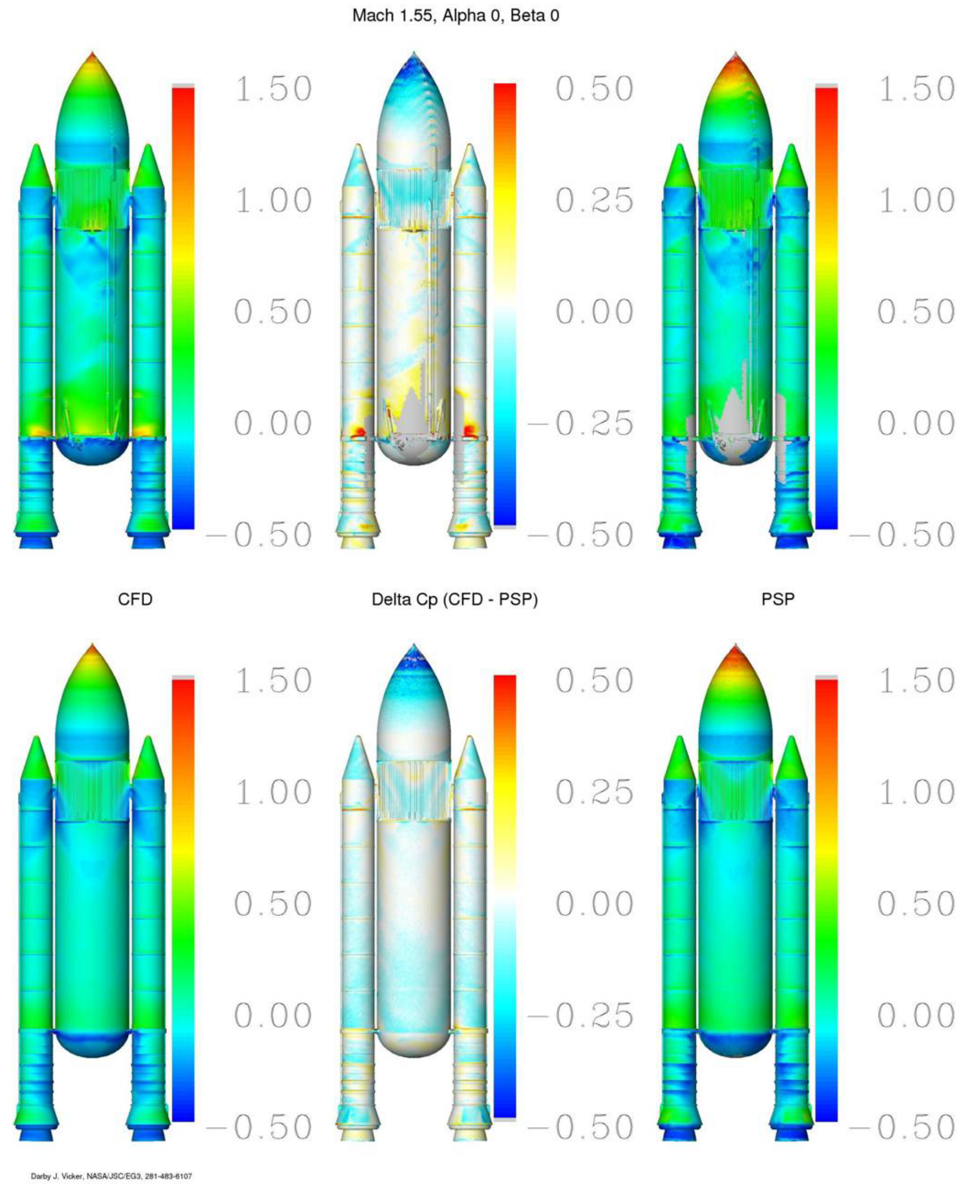


J. Greathouse/JSC

IA-700 Transonic PSP vs. CFD

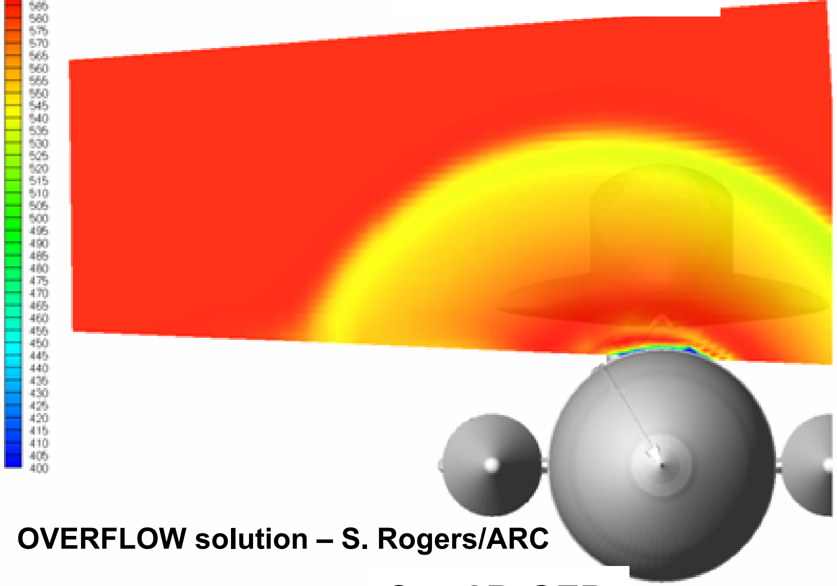
- Mach = 1.55, α = 0°, β = 0°
  - Lighting & camera angles reduced measurement quality in ET nose and Orbiter lower surface regions





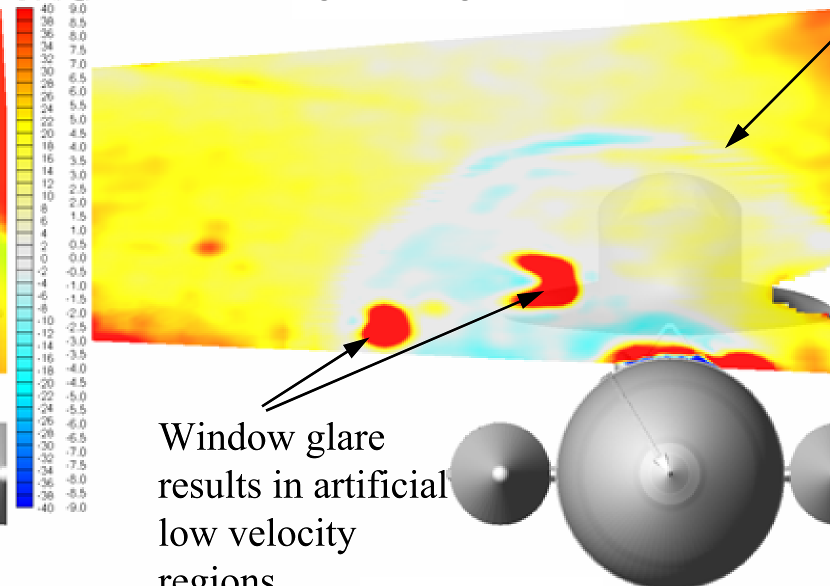
ARC 9 × 7 Mach 2.5 PIV Comparison

OVERFLOW CFD



OVERFLOW solution – S. Rogers/ARC

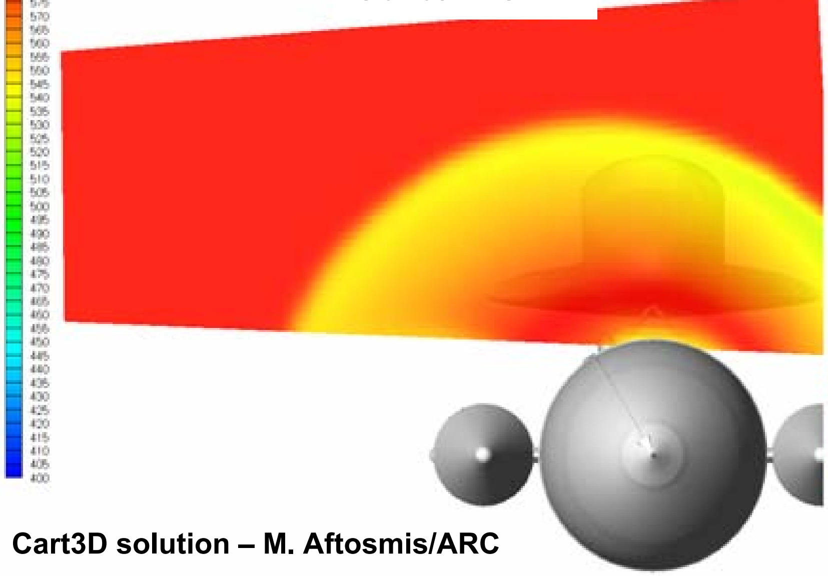
OVERFLOW - PIV



Optical distortion from ET bow shock caused PIV inaccuracies

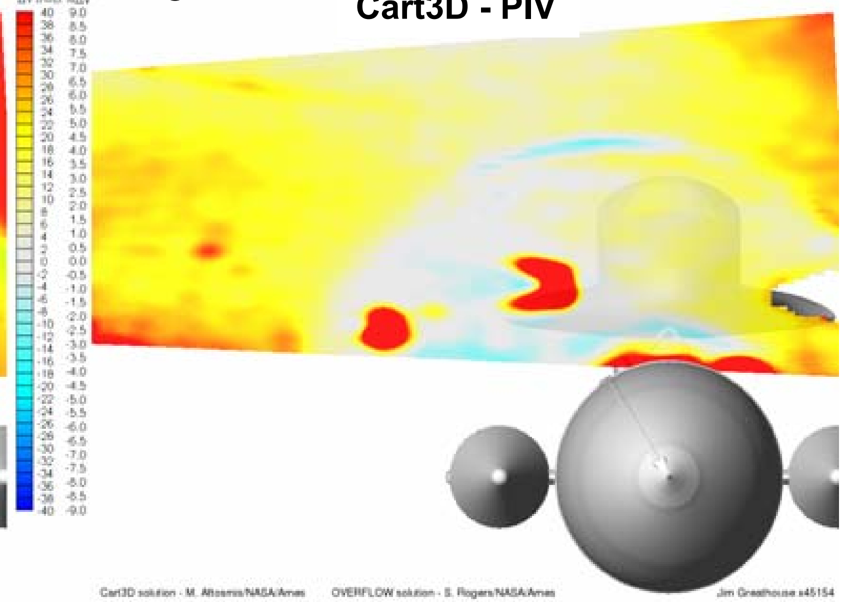
Window glare results in artificial low velocity regions

Cart3D CFD



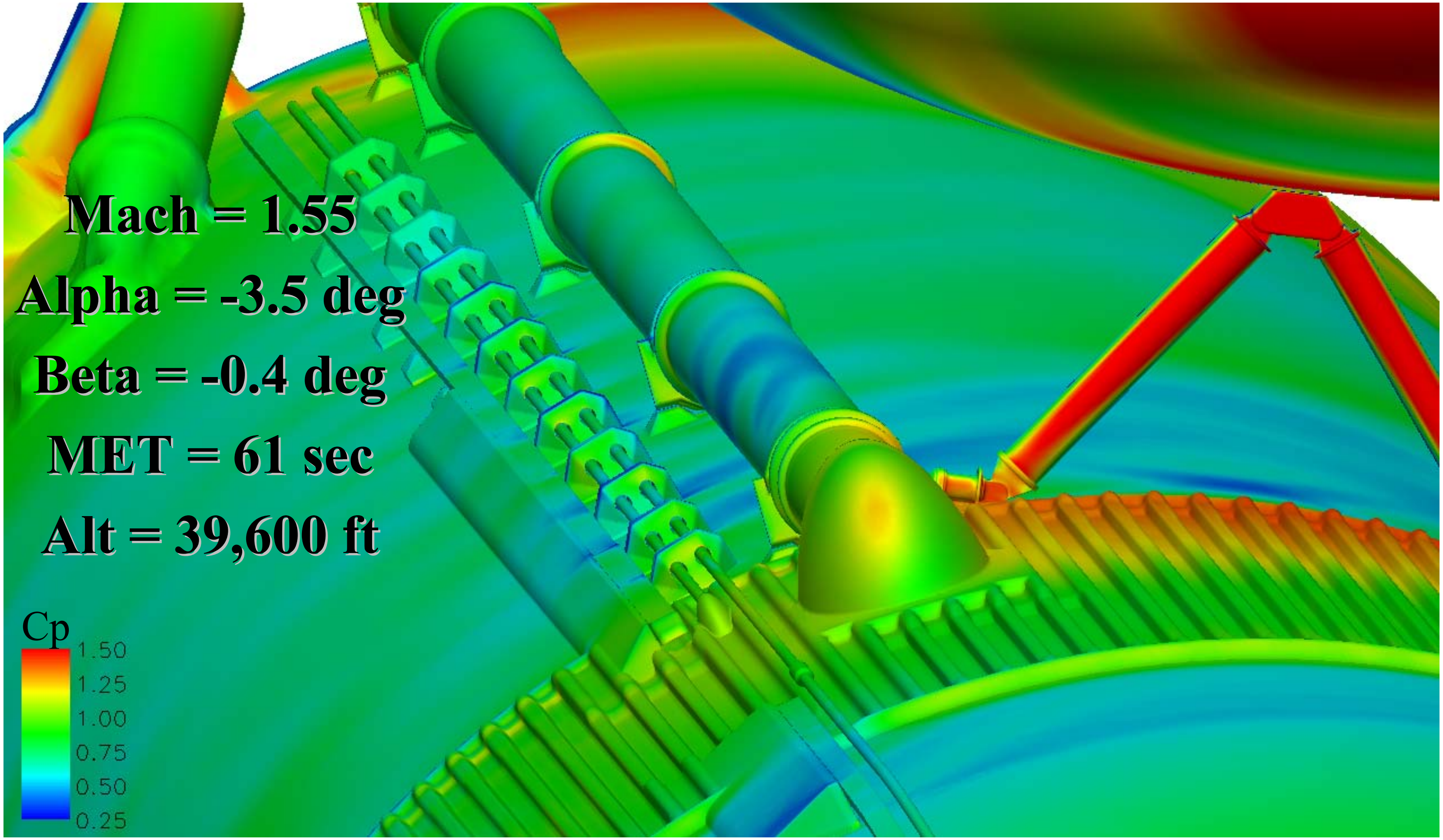
Cart3D solution – M. Aftosmis/ARC

Cart3D - PIV



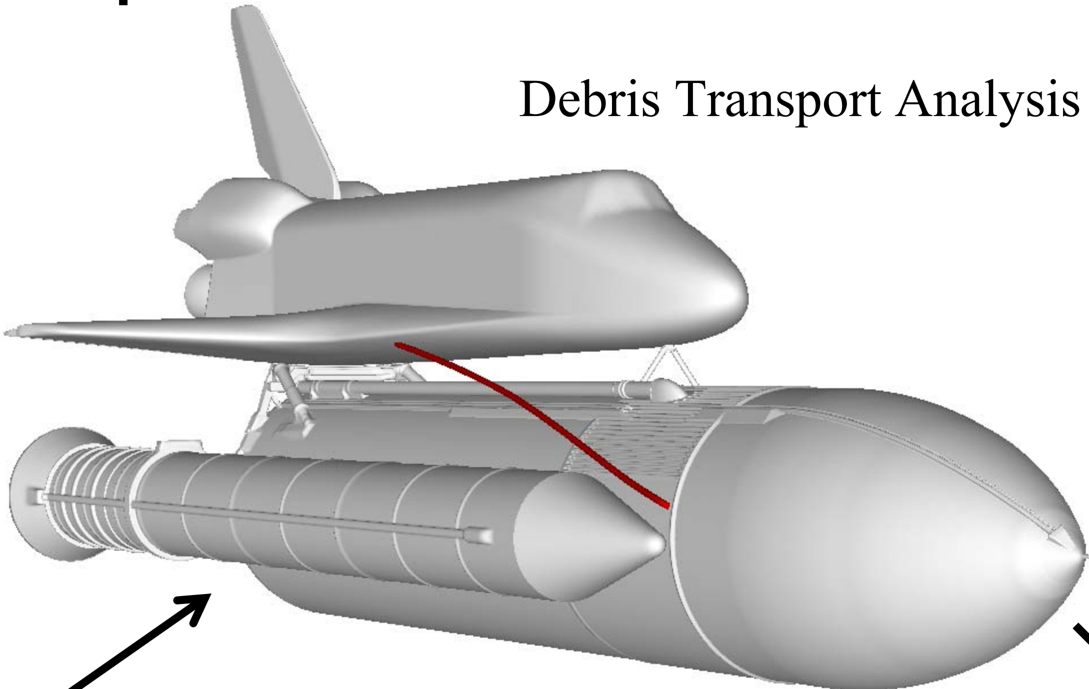
Post STS-114 Solutions

Addition of Ice/Frost Ramps

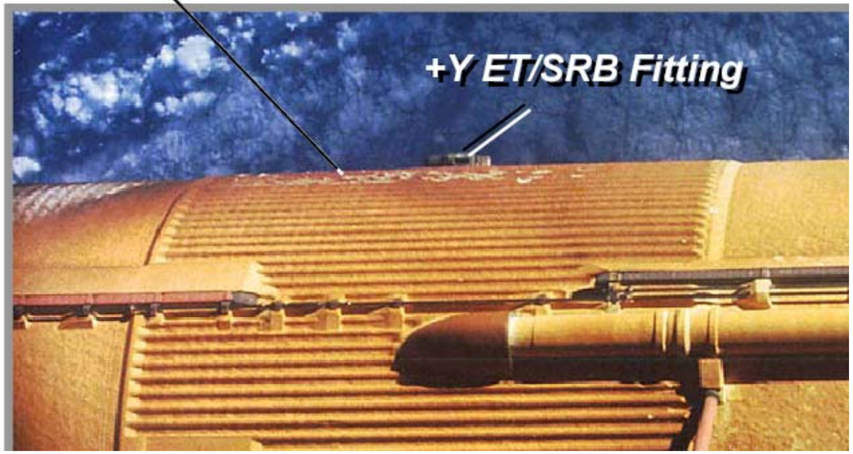


Debris Impact Assessment Process

Debris Transport Analysis



Debris Source



Damage Assessment

Debris Transport Process Overview

Debris Source/Outputs

- Material properties
- Installed geometry
- Likely debris shapes
- Failure mechanism, initial conditions

DTA Inputs

- Freestream conditions
- CFD-based flowfield
- Debris aerodynamic models
- Vehicle Geometry

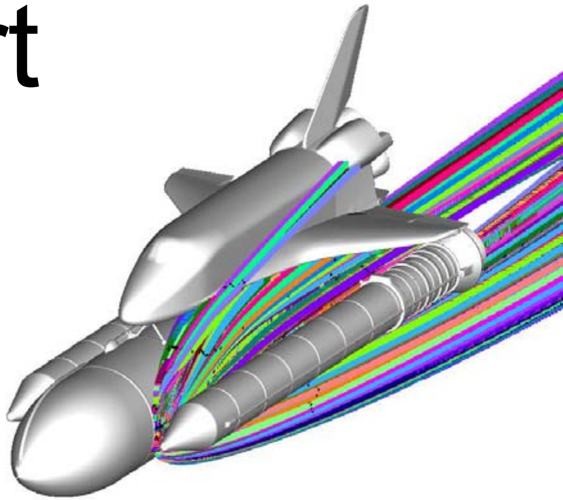
DTA Environment

- Impact location, mass, velocity, incidence angle
- Rotation rate

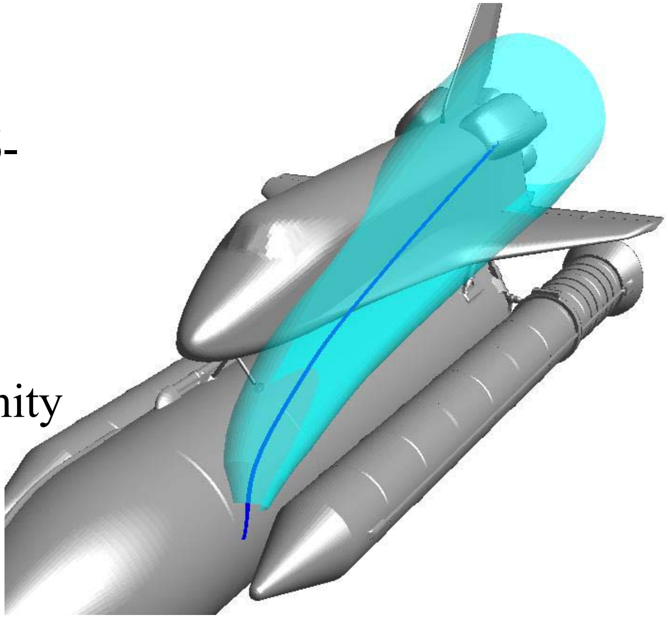
Element Impact Capability

- Material properties
- Installed geometry
- Impact tolerance
- Damage tolerance

Debris Transport

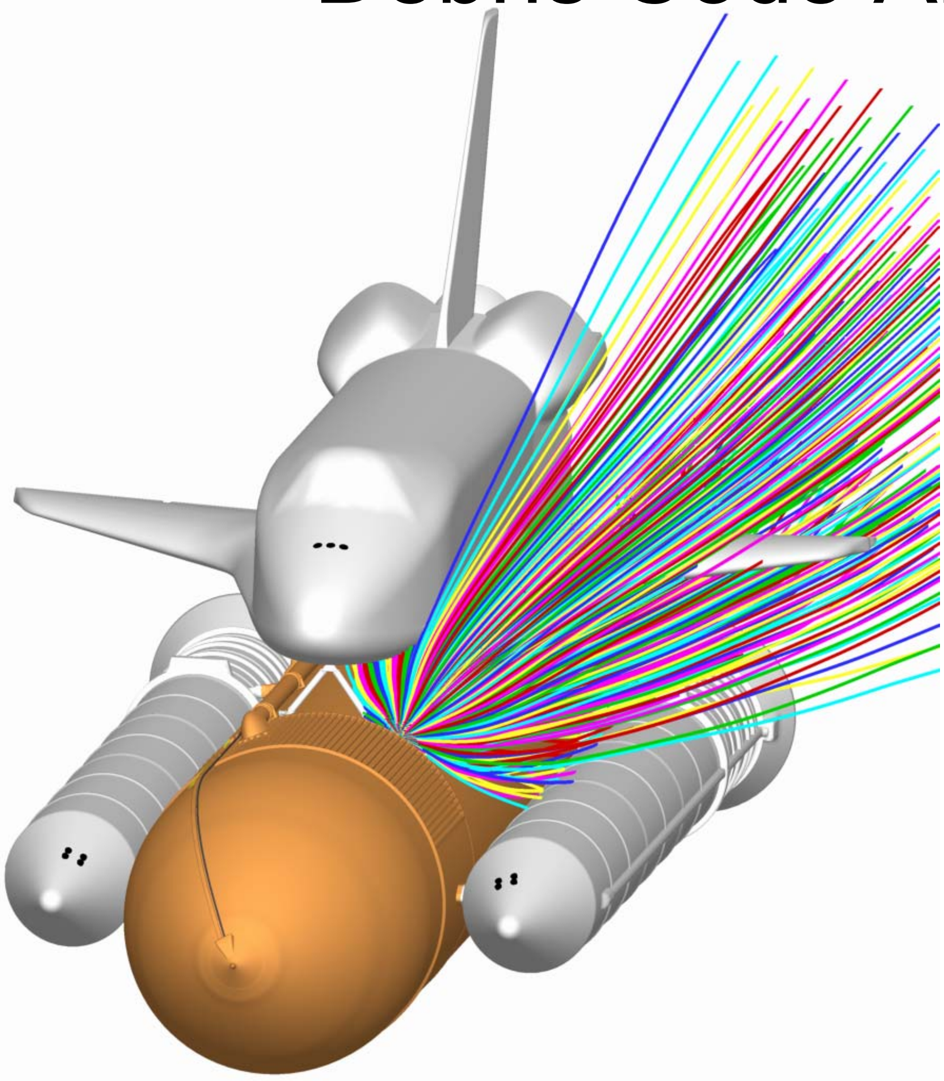


- Ballistic debris integration:
  - Steady-state CFD flowfield
  - Integrate motion of point-mass subject to drag force due to relative local wind vector at current location in the flowfield
  - Neglects effect of cross-range dispersions due to lift
- Debris Transport software development:
  - Developed debris-drag models using Cart3D 6-DOF unsteady simulations
  - Significant improvements to debris-trajectory computations
  - Wrote software for debris collision and proximity detection
  - Wrote general purpose sorting and filtering of collision output

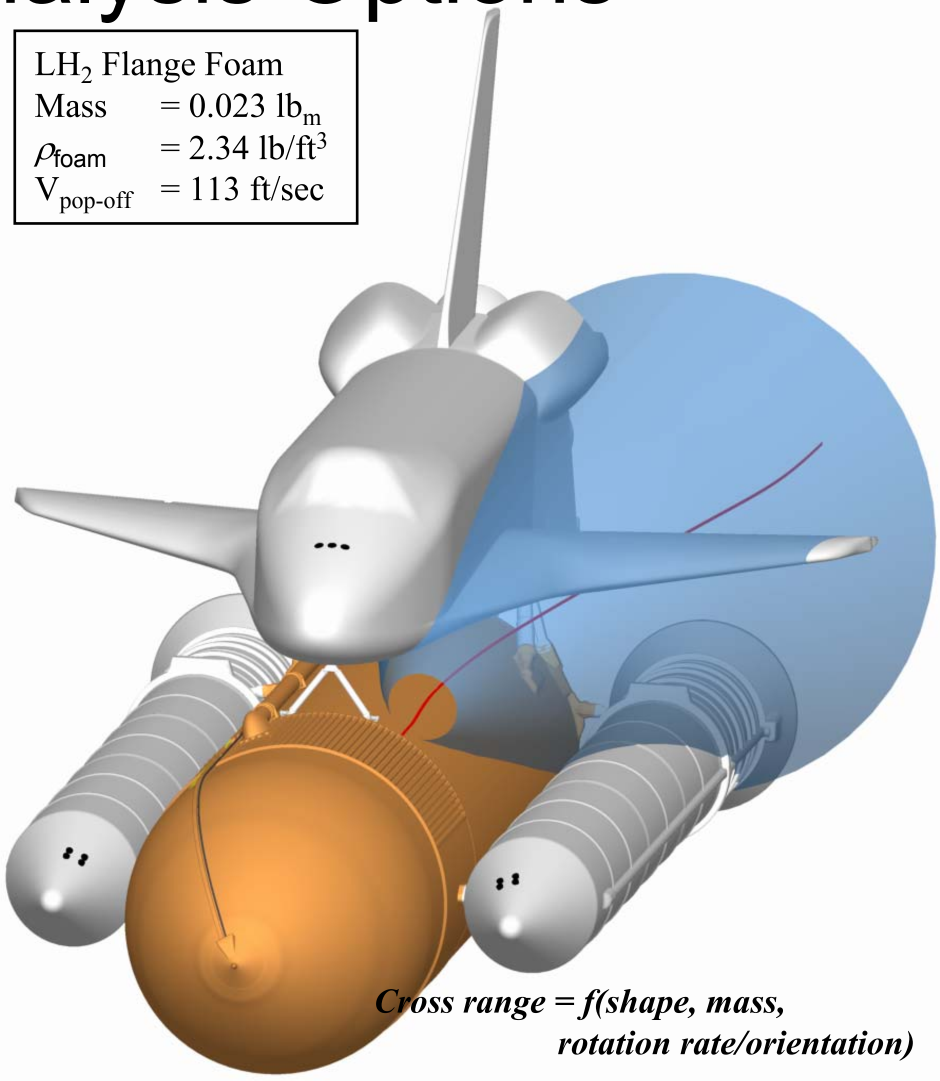


- Millions of debris trajectories have been computed and analyzed

Debris Code Analysis Options

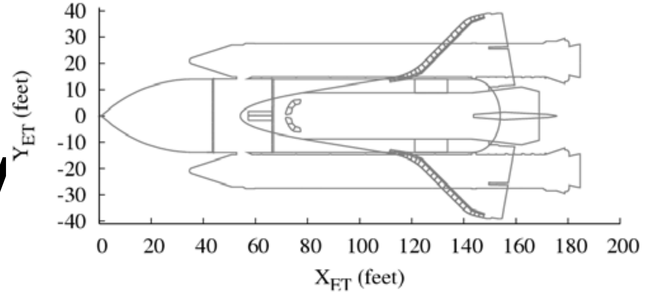


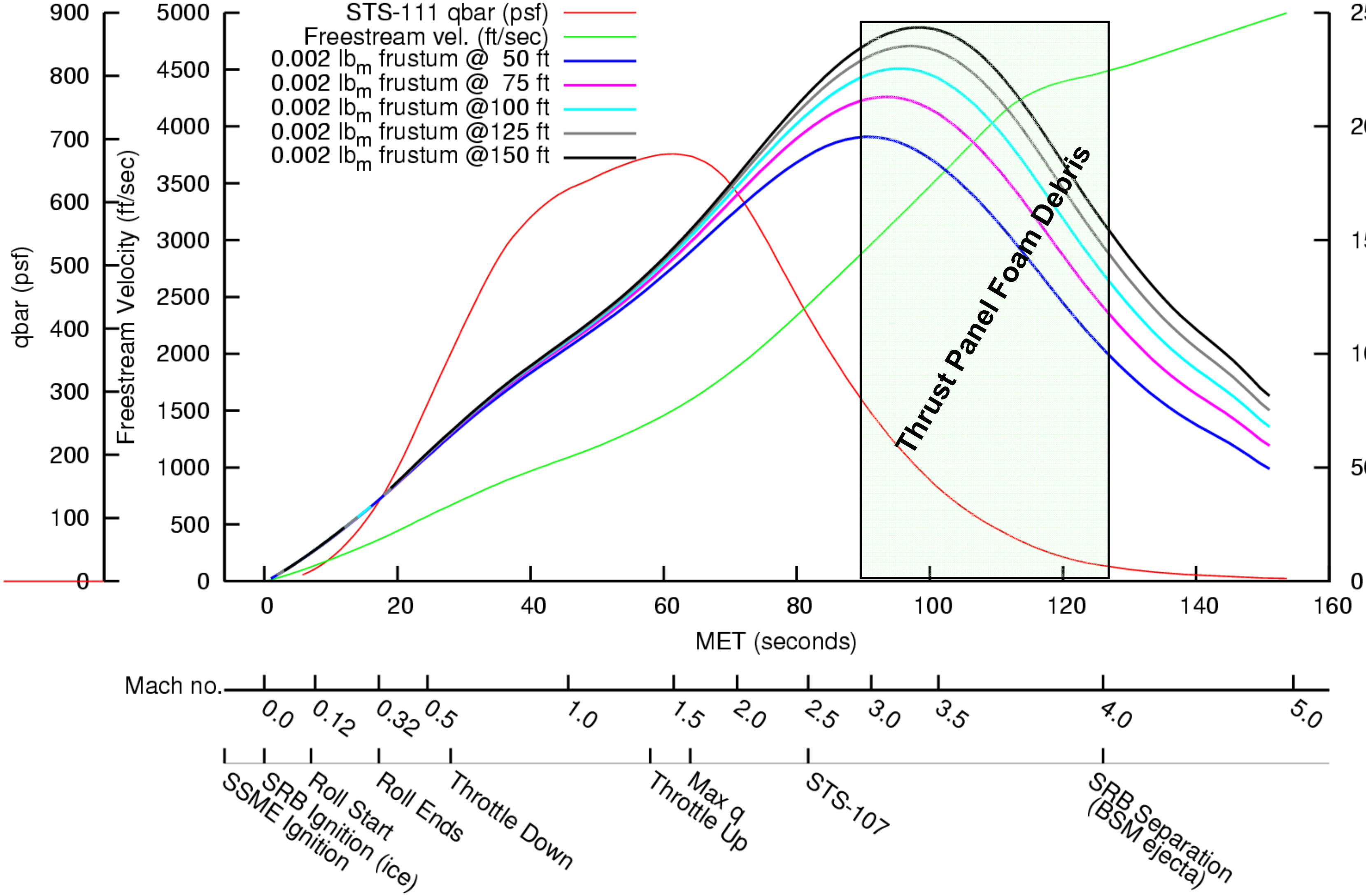
Deterministic
Zero Lift Trajectory + Range of Initial Velocities



Probabilistic
Zero Lift Trajectory + Crossrange Cone

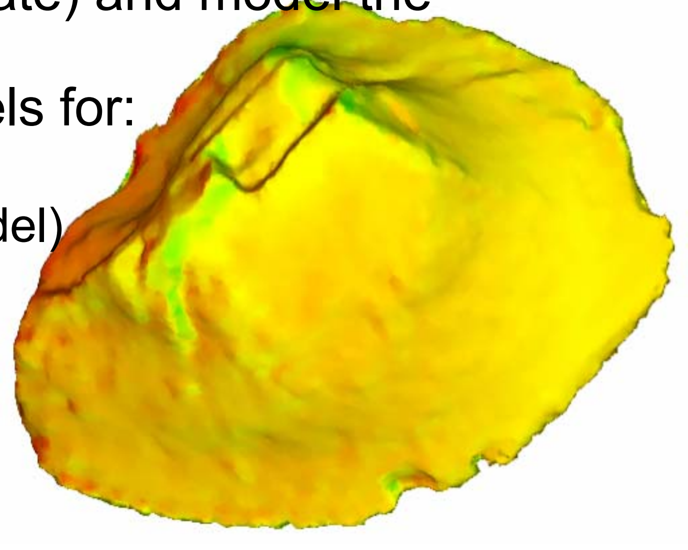
Time History





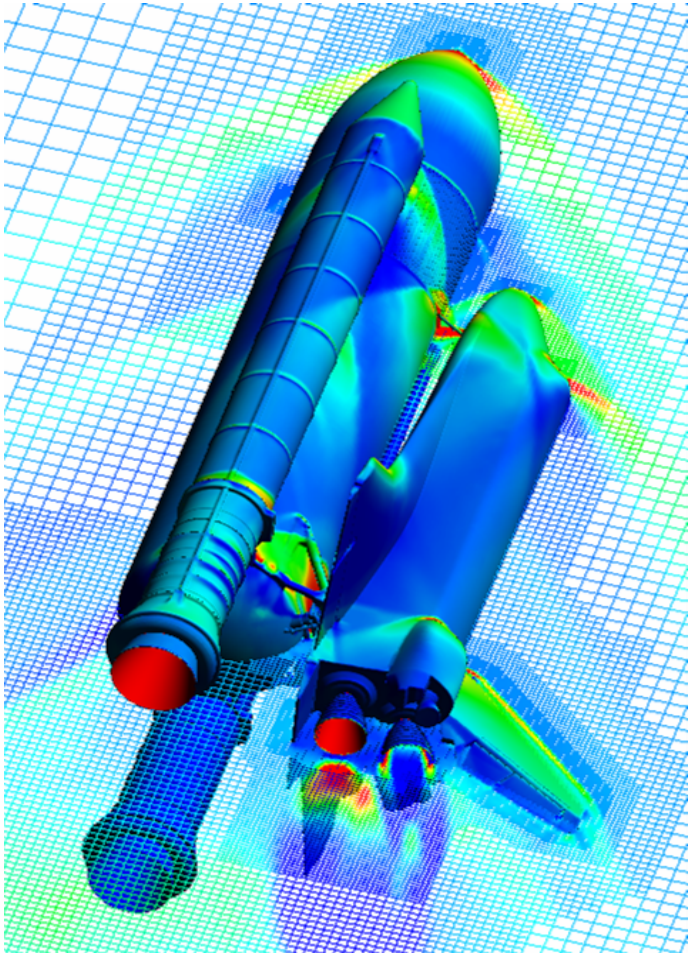
Debris Aerodynamics Modeling

- Debris Transport currently requires two aerodynamic models for each type of debris to be analyzed:
  - **Drag model :** determines impact velocity
  - **Cross-range model** : determines impact locations
- Impractical to determine model parameters using experimental techniques (too costly, time consuming, restricted to simple shapes).
- Use validated CFD methods (cheap, rapid turnaround, not restricted by geometry shapes).
- Compute hundreds of 6-DOF trajectories using a Monte-Carlo approach (vary shape, orientation, rotation rate) and model the resulting behavior.
- Have developed drag and cross range models for:
  - Tumbling cube
  - Foam divots (based on a conical frustum model)
  - Ablator material
  - Hemisphere, to model ice balls



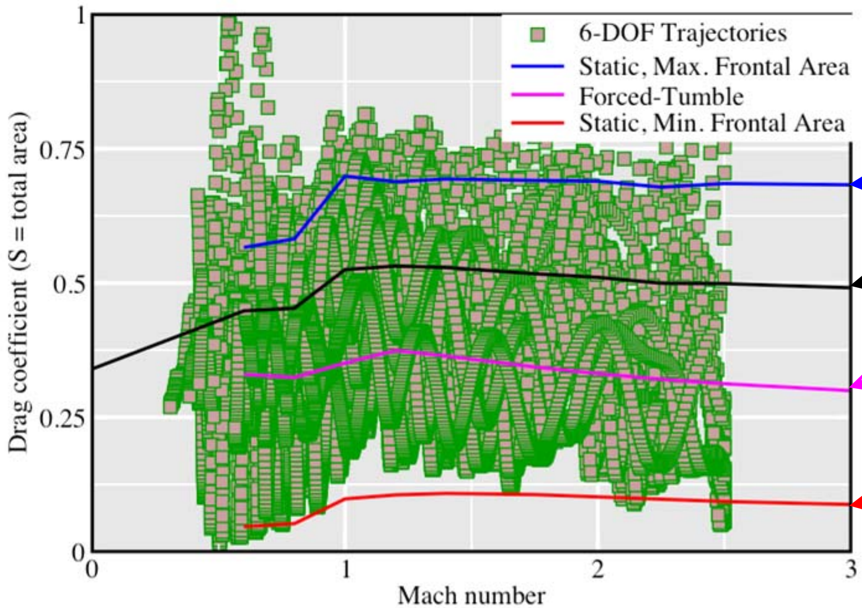
Cart3D

- Automated mesh generation from CAD
- Partitioned on the fly for any number of CPUs
- Solves Euler equations:
  - Unstructured Cartesian cells
  - Finite-volume formulation
  - Multi-grid acceleration
  - Shared-memory parallelization w/ OpenMP
  - 4.5 million cells, 15 levels of refinement

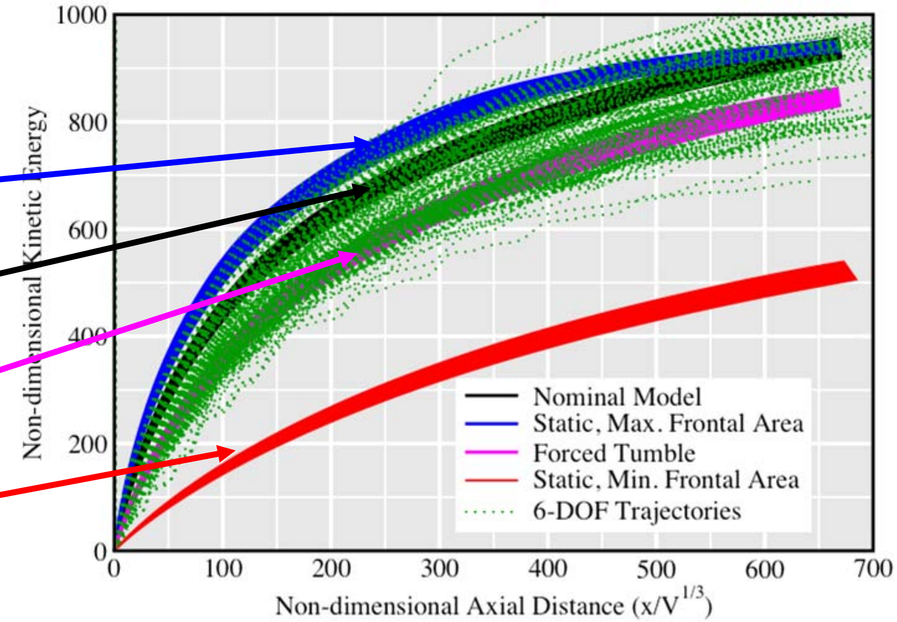


- Drag modeling uses 6-DOF data
- Kinetic energy (damage potential) used as "fitness function"
- Drag model validated against Ames GDF range data
  - Drag models created Feb. '04
  - These models were used in the design of all the validation experiments

Drag

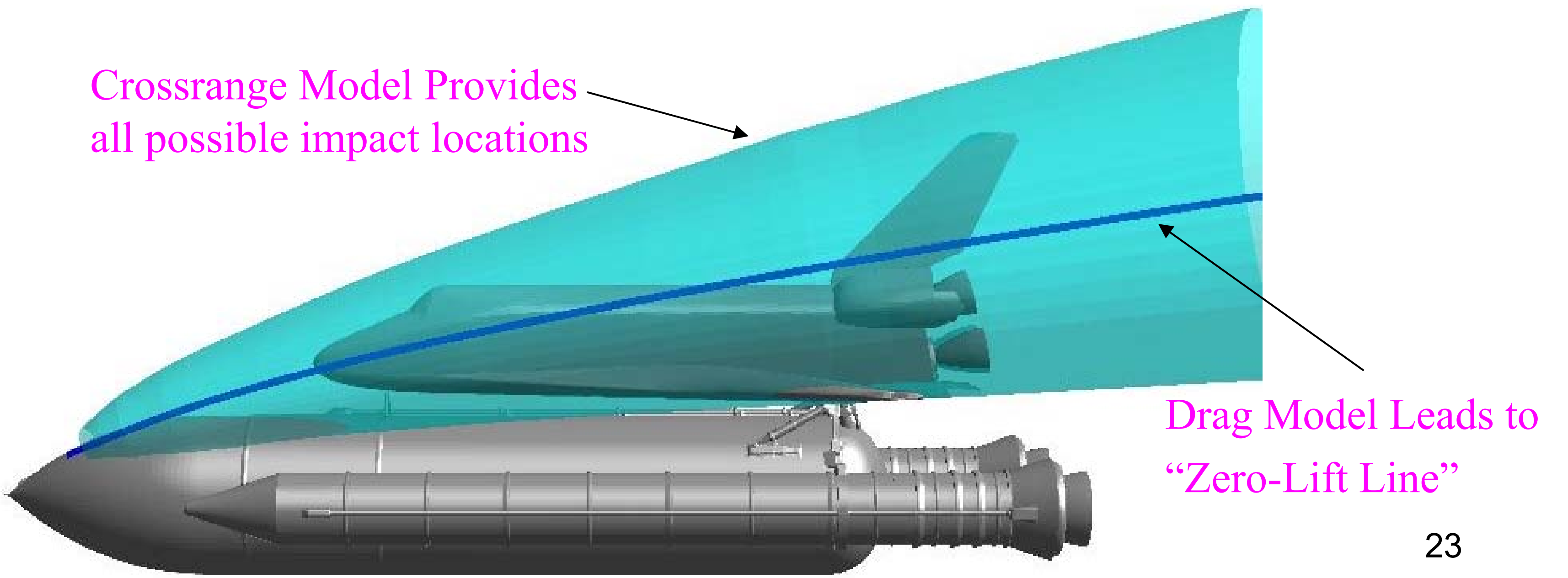


Kinetic Energy



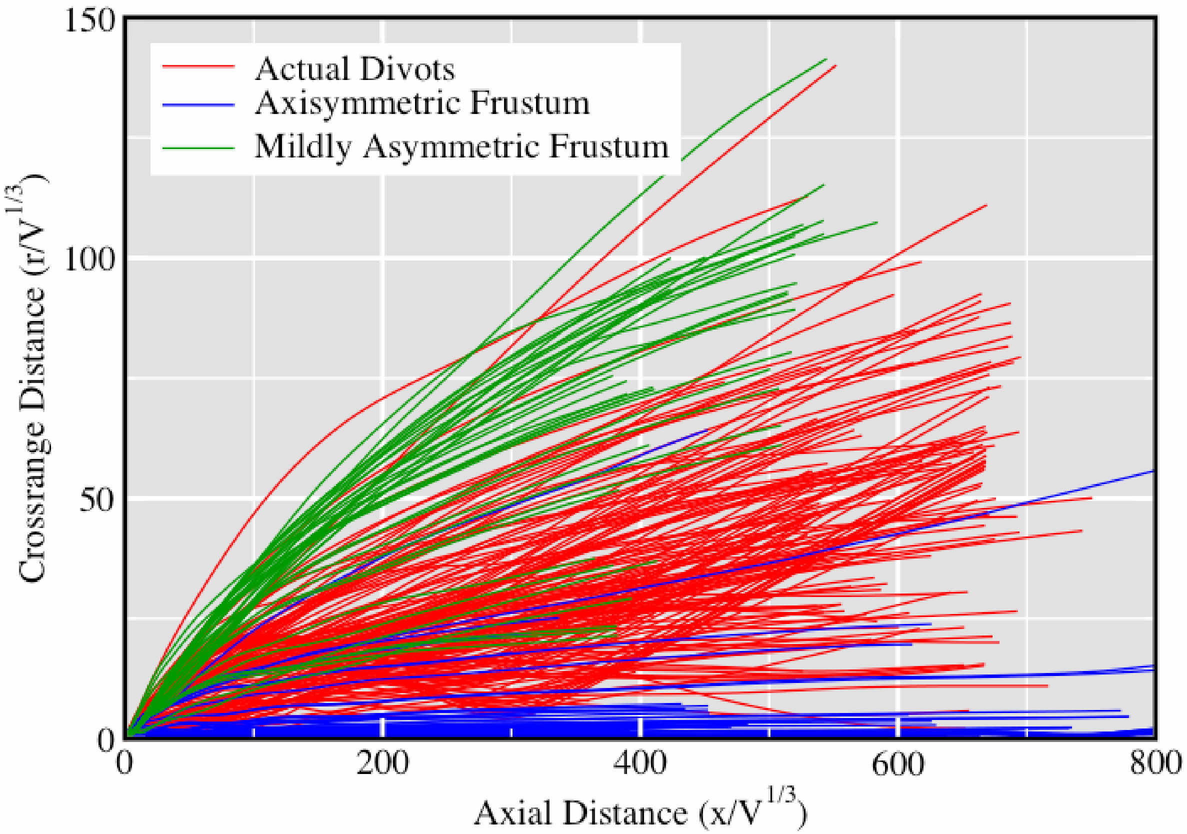
Foam Cross-Range Model

- Debris can generate aerodynamic "lift" in arbitrary direction during trajectory (referred to as crossrange).
- This effect is modeled in a post-processing step.
- Crossrange cone applied to zero-lift debris trajectories from ballistic code to determine possible impact points.



Foam Cross-Range Data

- ❑ Data from Monte-Carlo CFD 6-DOF trajectories used to develop crossrange cone.
- ❑ Several shapes used to develop crossrange behavior.
- ❑ Results can be scaled to arbitrary-sized debris.
- ❑ A probability can be assigned to any location within crossrange cone.

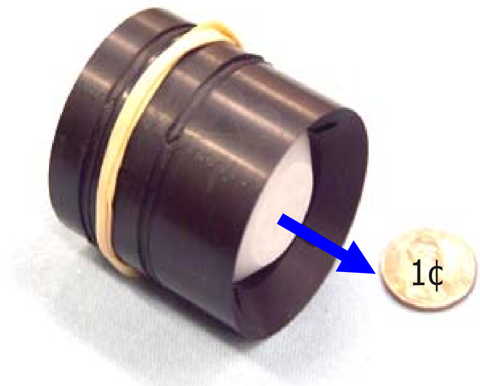


Validation With Gun Development Facility (GDF) Data

- There are two aspects to the validation effort:
  - Validate the ability of the Cart3D code to simulate a 6-DOF foam trajectory by direct comparison against range data. (validation of CFD method)
  - Validate the foam drag and cross-range models using the range data. (validation of models)

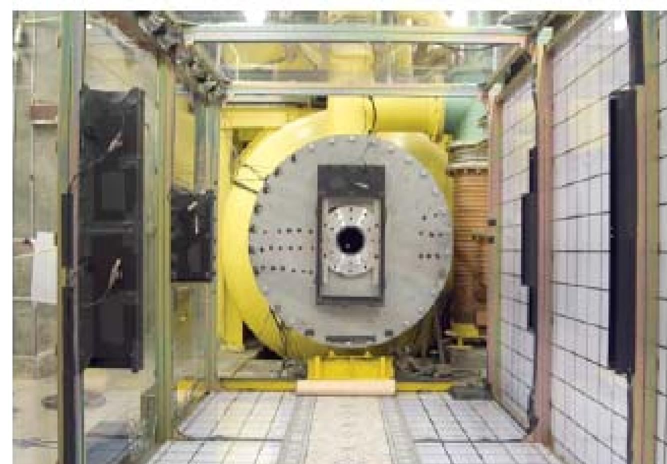
Ames Gun Development Facility

1.75” Powder Gun and Dump Tank



Sabot and Projectile

Side-View Cameras and Controllers



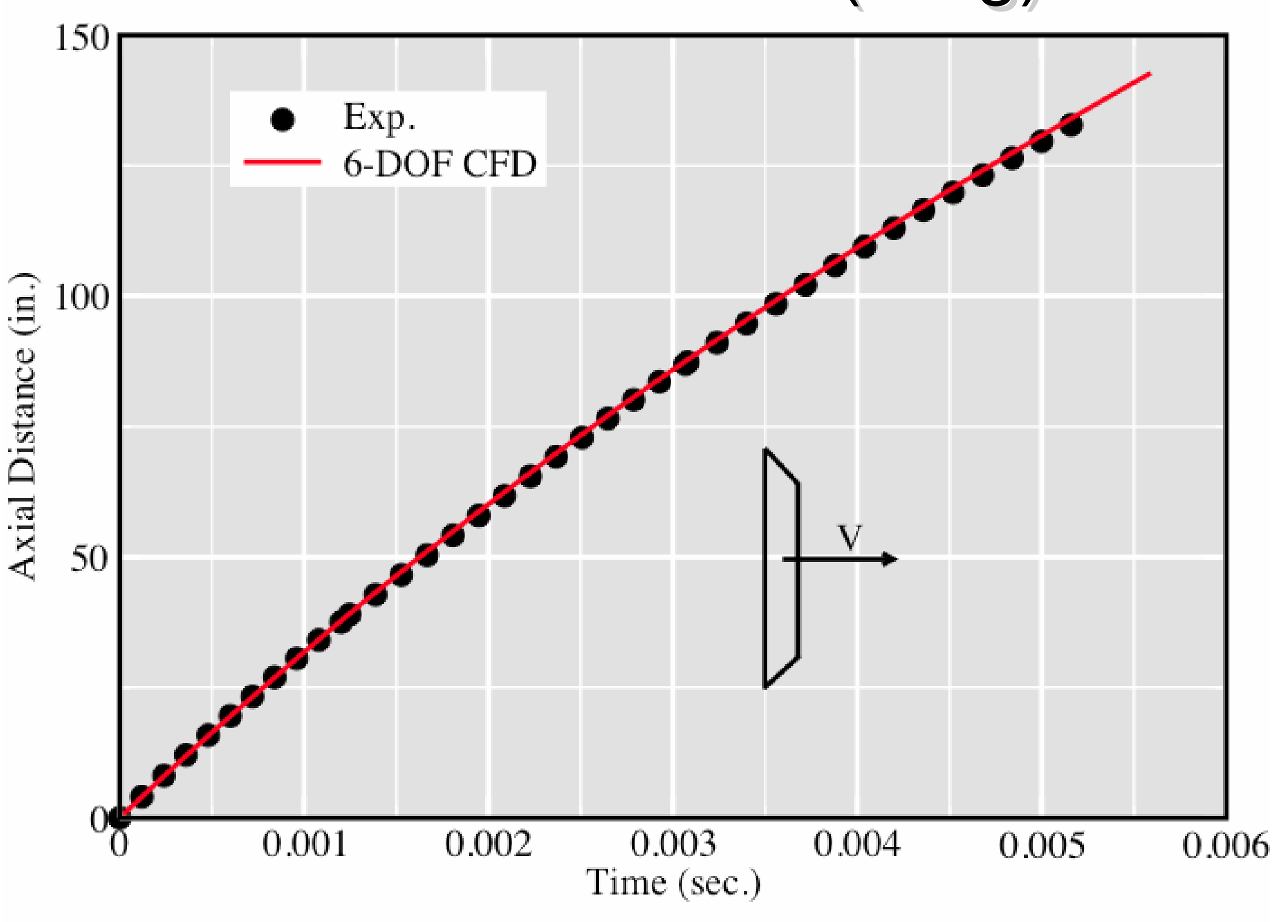
Test Section - Diaphragm, Lights, Light Screens, and Calibration Grids

Jeff Brown - Eloret/Code ASA
650-604-6192 / jbrown3@mail.arc.nasa.gov

6-DOF Method Validation
Ames GDF ballistic data Distance vs Time

- Mach 2.51, 6000 g's deceleration

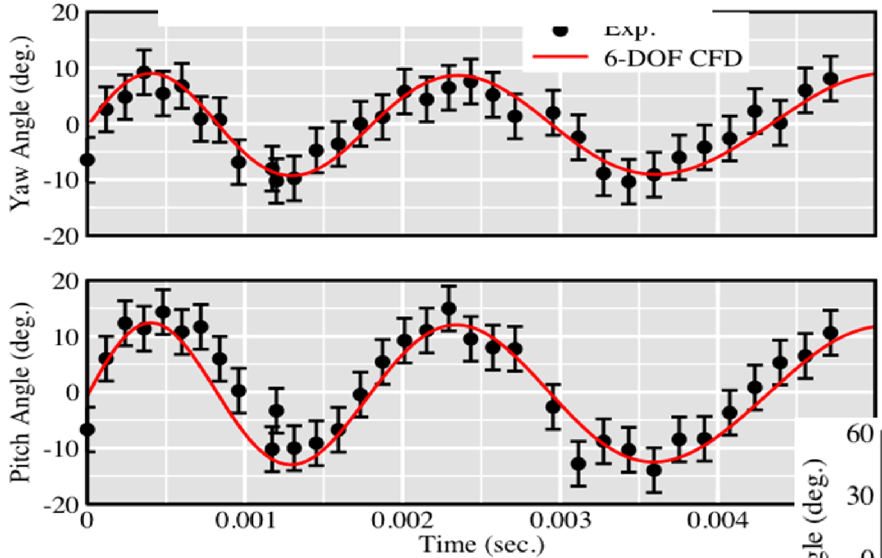
Axial Distance (Drag)



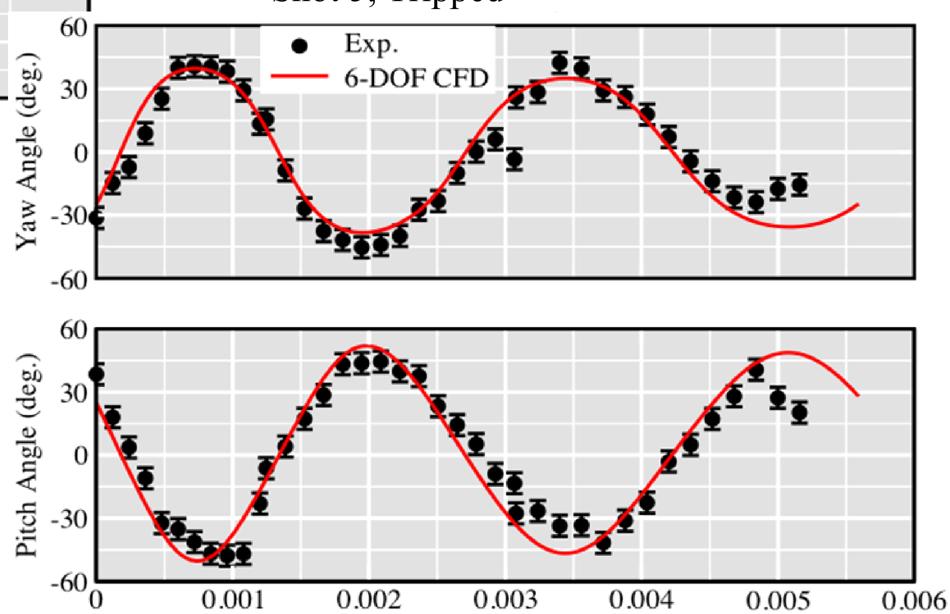
6-DOF Method Validation

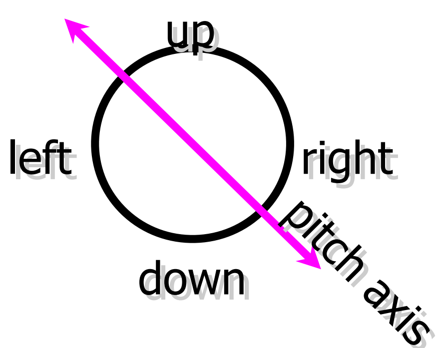
Ames GDF ballistic data Pitch/Yaw vs Time

Shot 3, Untripped



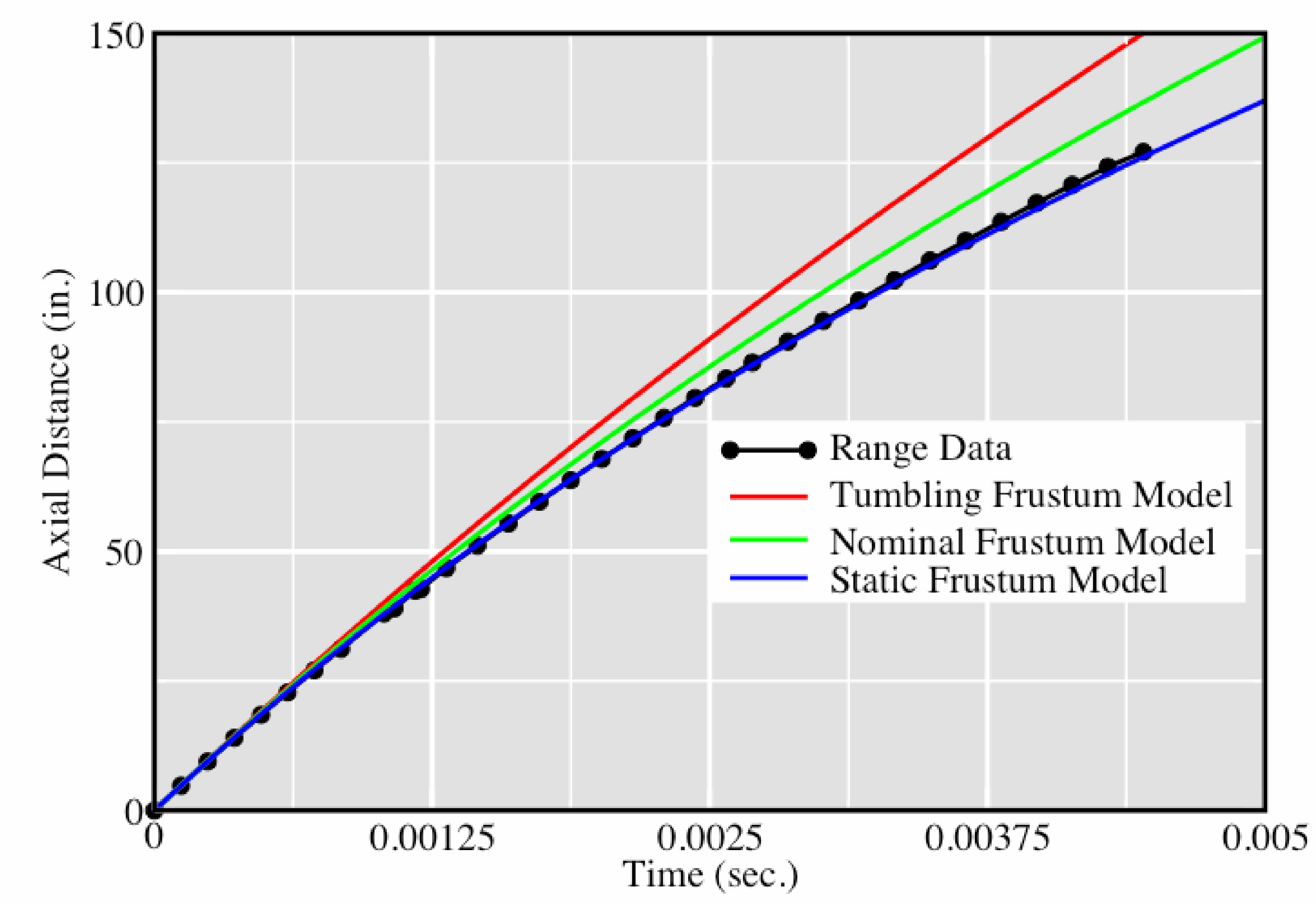
Shot 5, Tripped





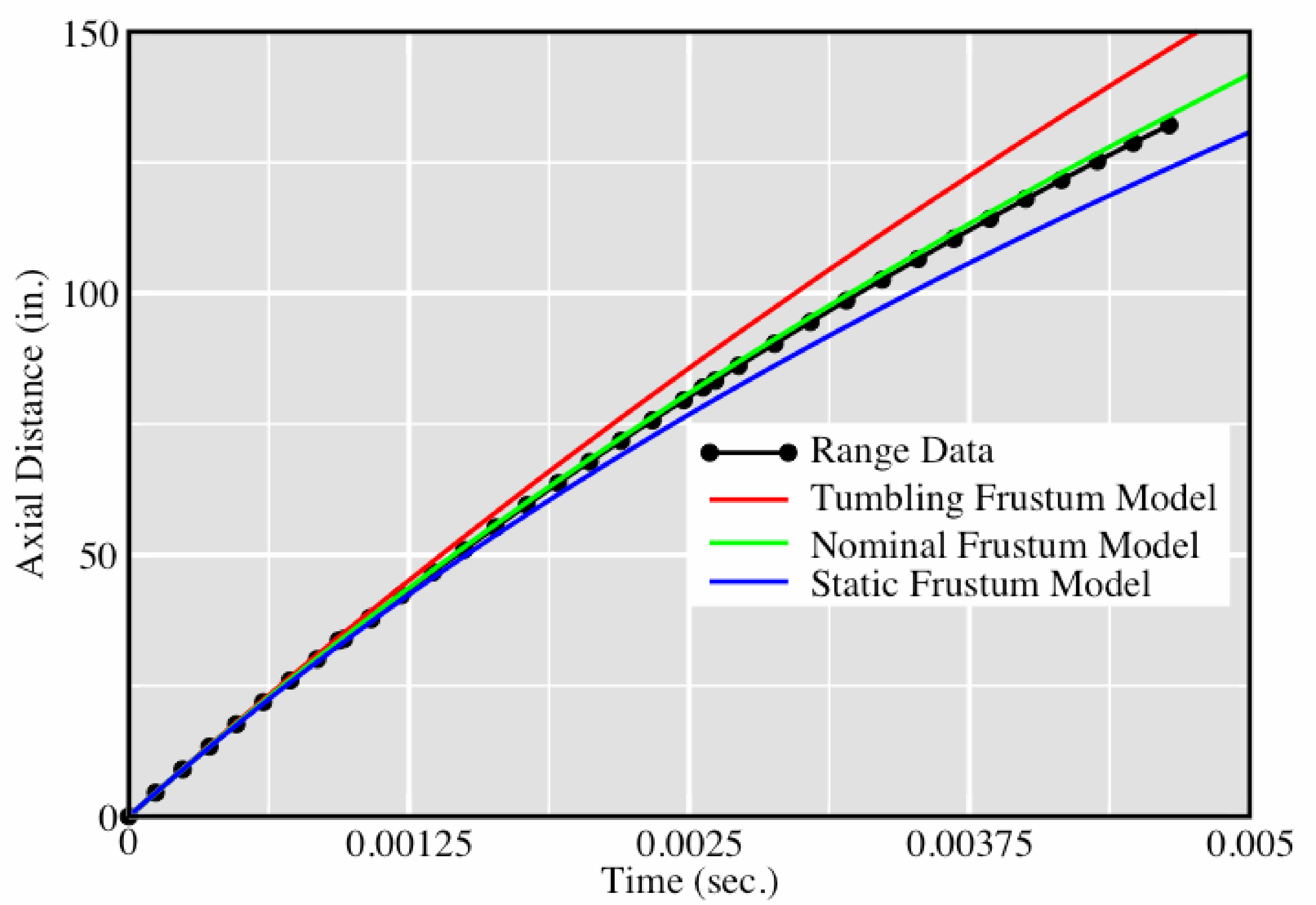
Drag Model Validation

- Low oscillation trajectory - shot 2, Mach = 3.00



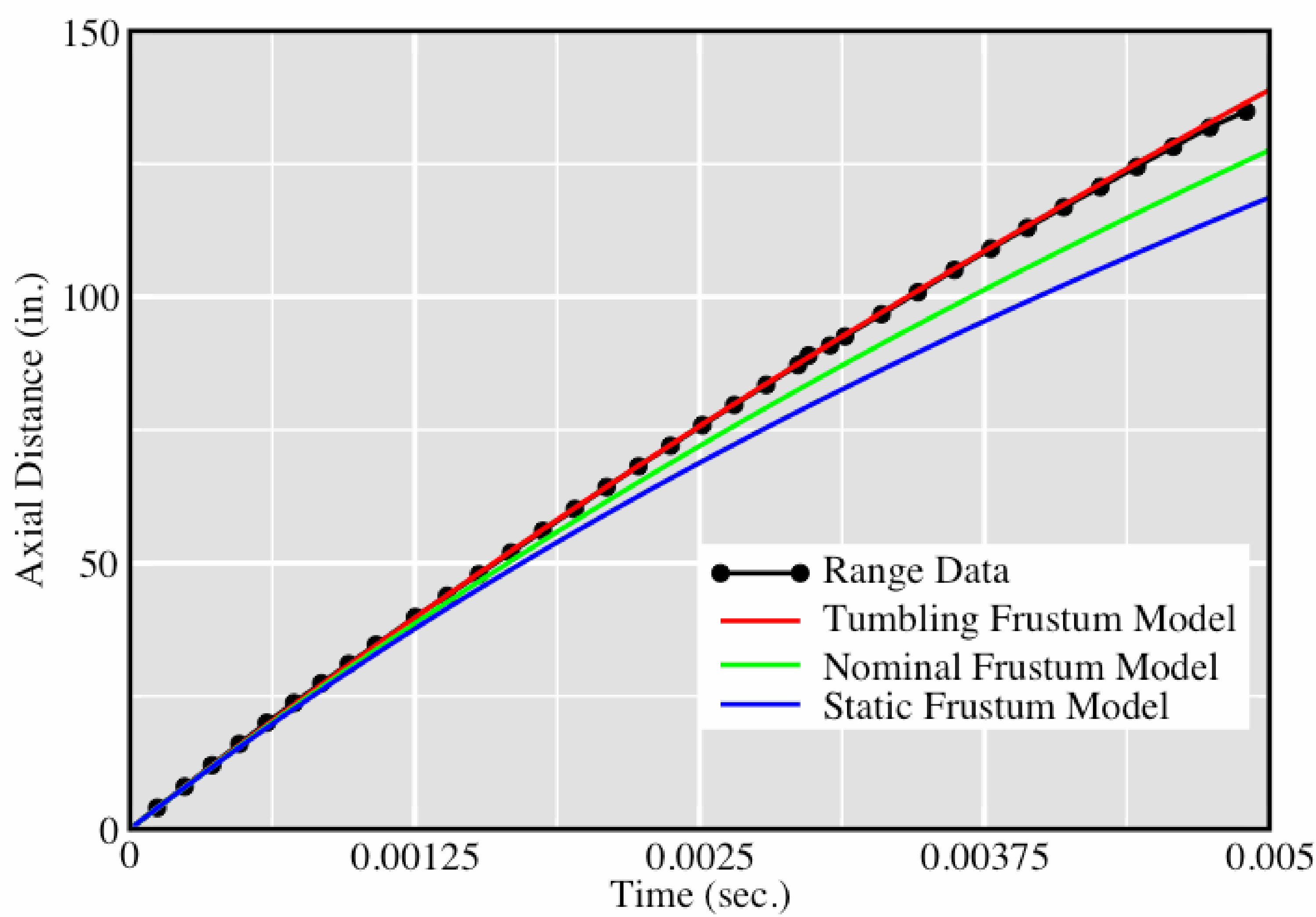
Drag Model Validation

- Medium oscillation trajectory - shot 7, Mach = 2.81



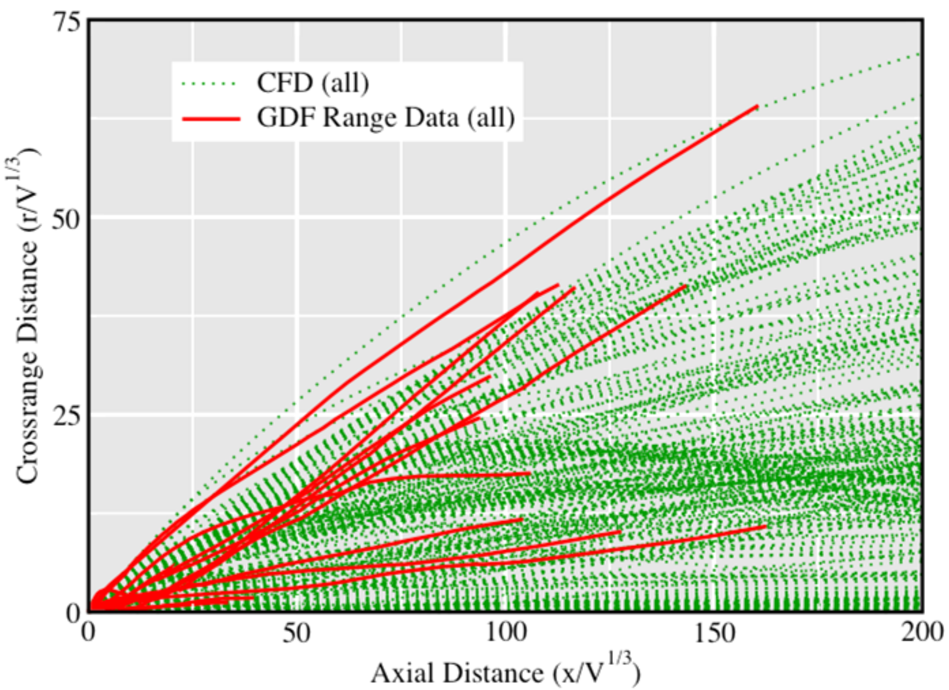
Drag Model Validation

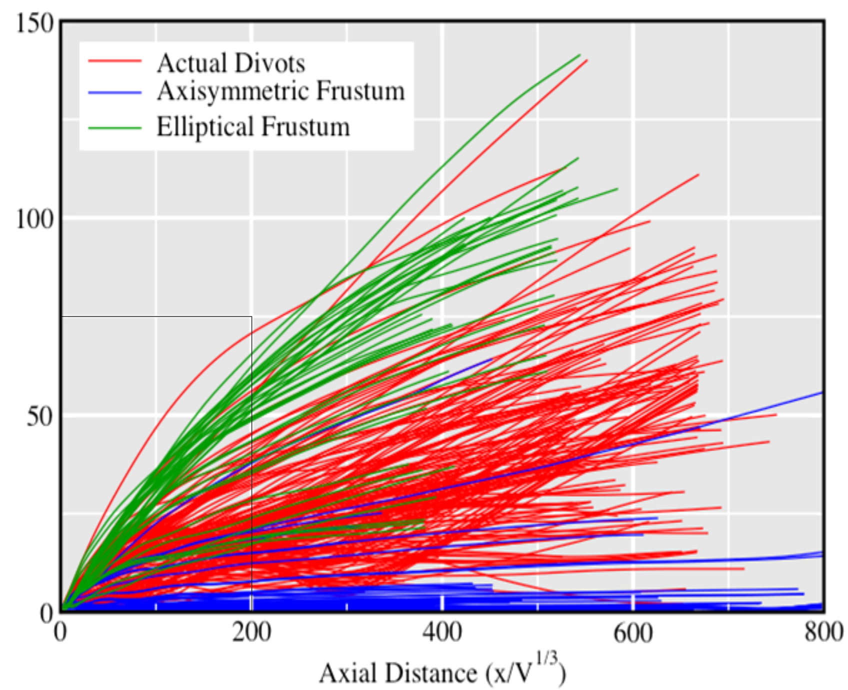
- High oscillation trajectory - shot 6, Mach = 2.46



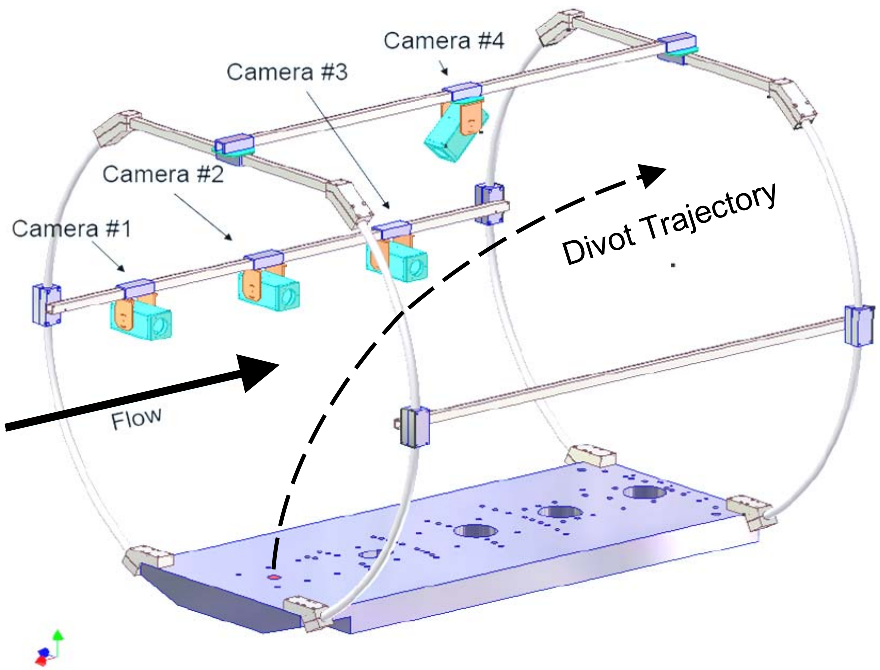
Crossrange Validation

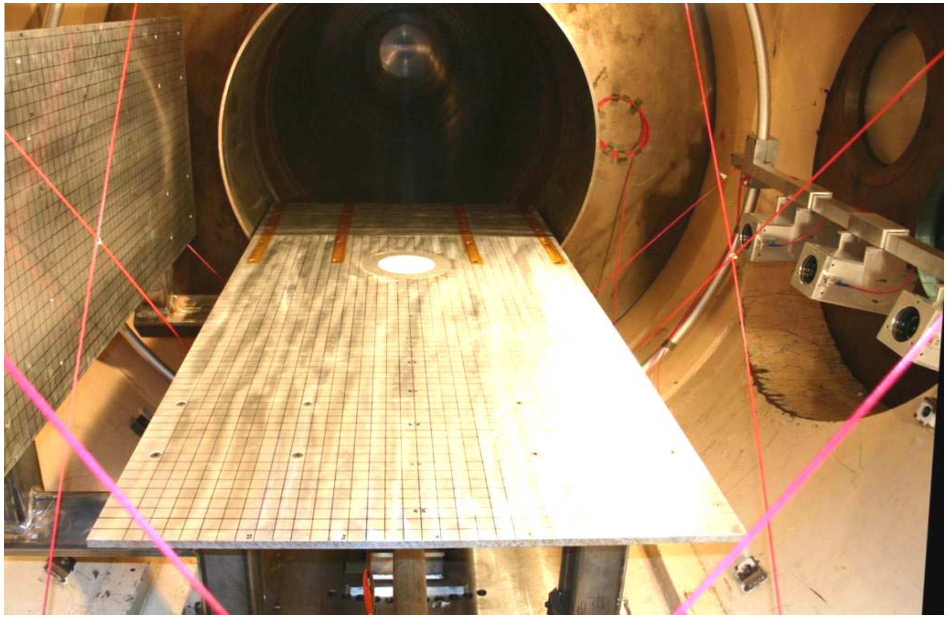
- Cart3D 6-dof predictions bound ballistic data
  - CFD (all) represents several hundred CFD trajectories generated from offset C.G. and asymmetric models
    - CFD data is used in dprox code to determine potential impact cone
- Even mild asymmetry generates strong crossrange



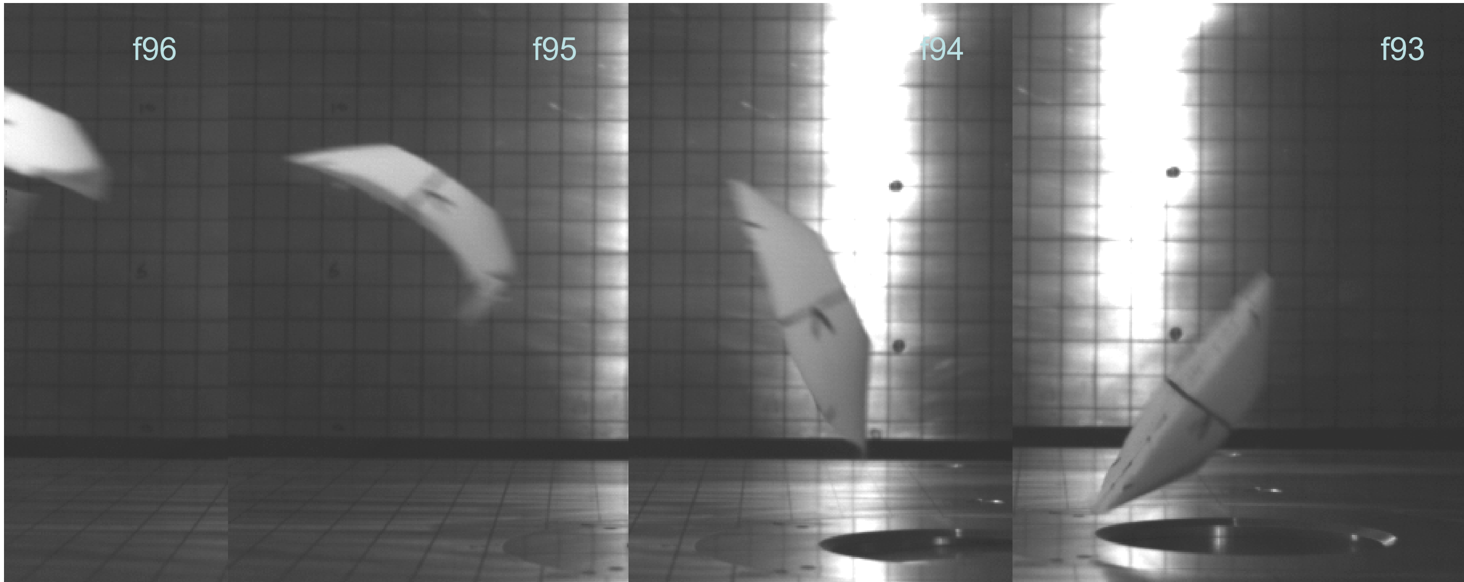


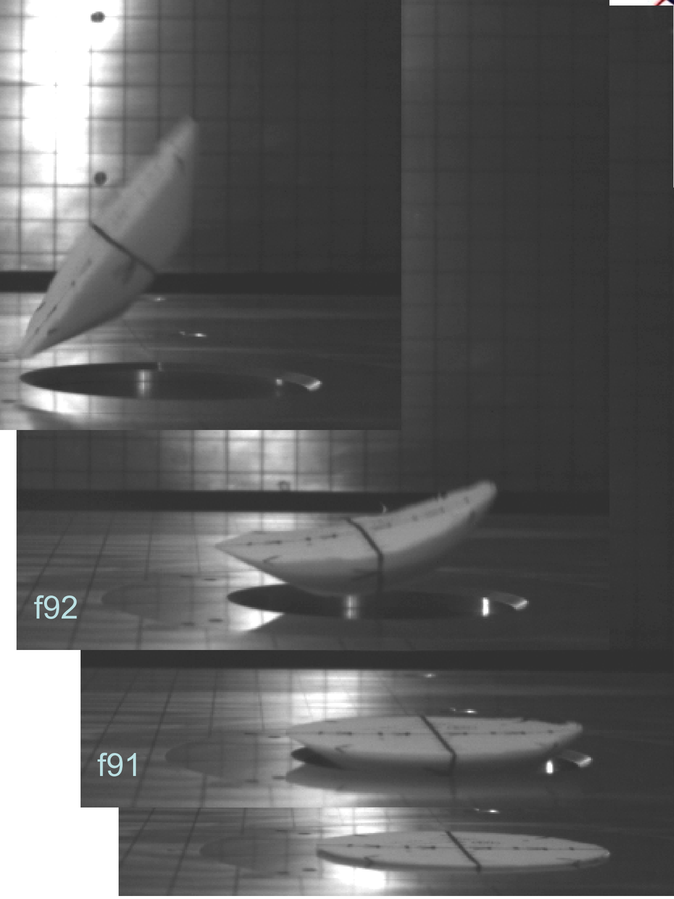
CUBRC Setup





View looking back upstream





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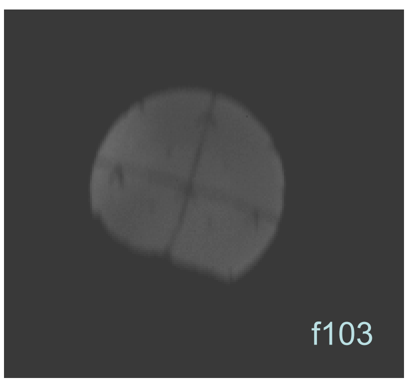
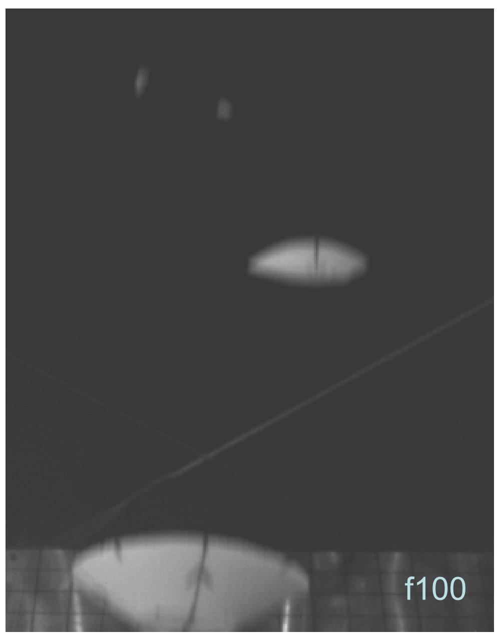
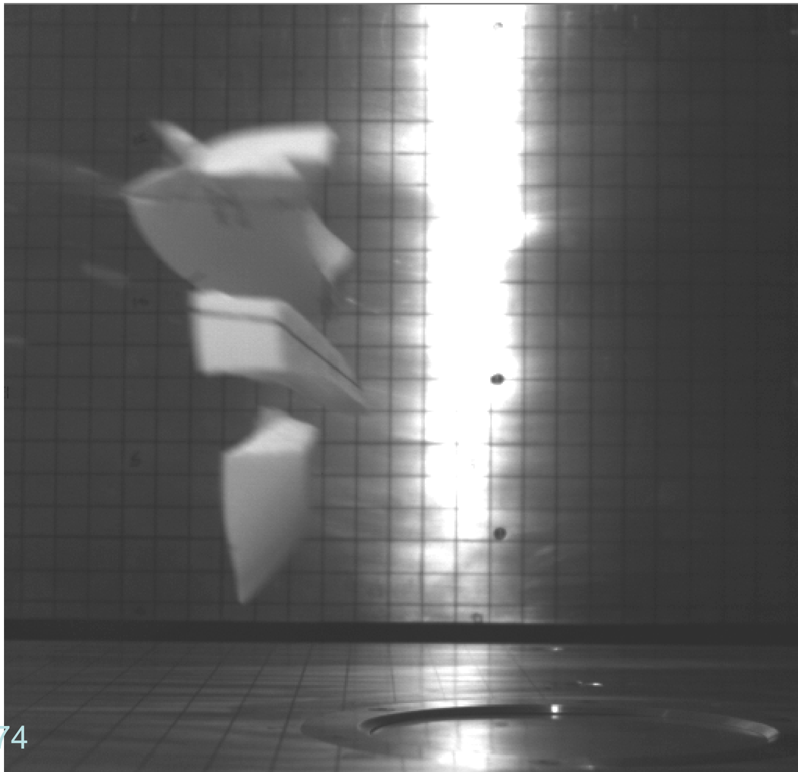




What the two pieces looked like several feet down stream

Run 9
5.1 inch divot AR 5.4
Mach 3.5 Q 706 psf

Run 12
7.4 inch divot
AR 7.8
Mach 3.5
Q 729 psf



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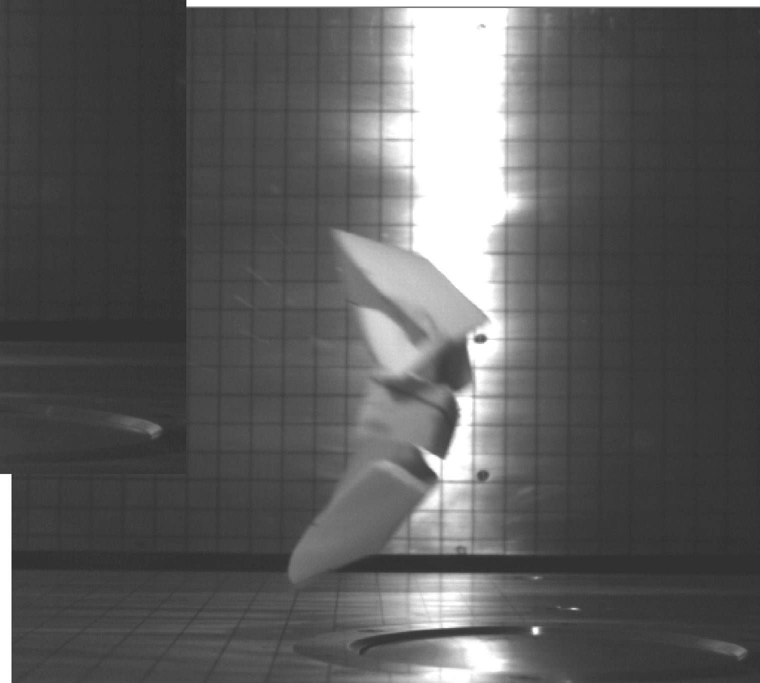
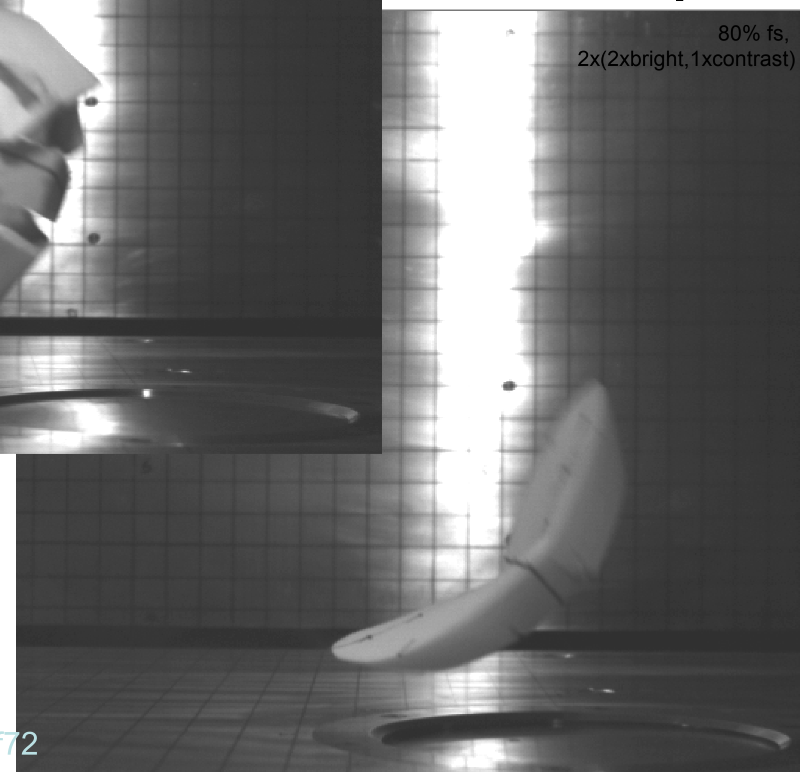


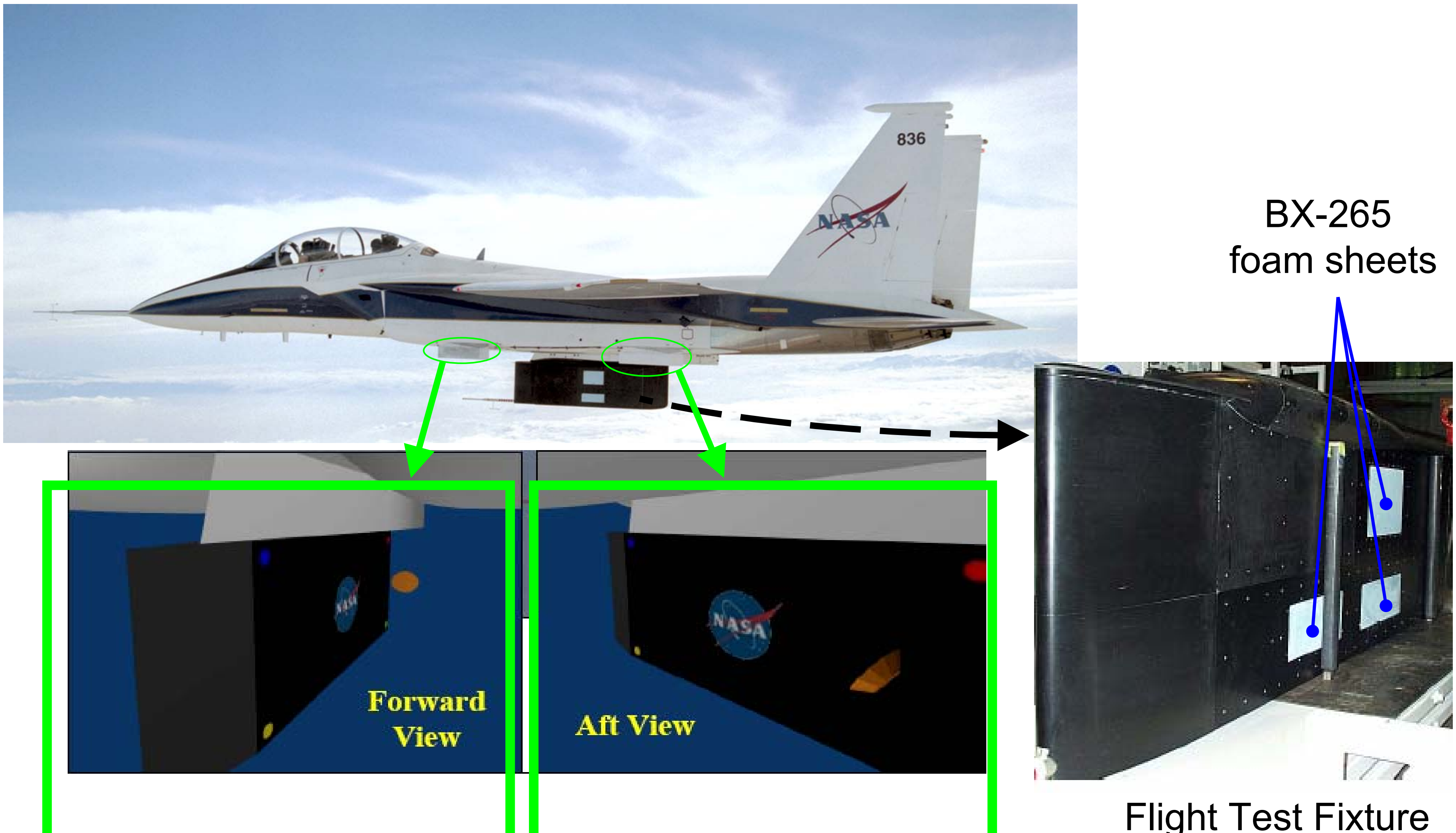
f73

Run12$_{-h1}$



f72

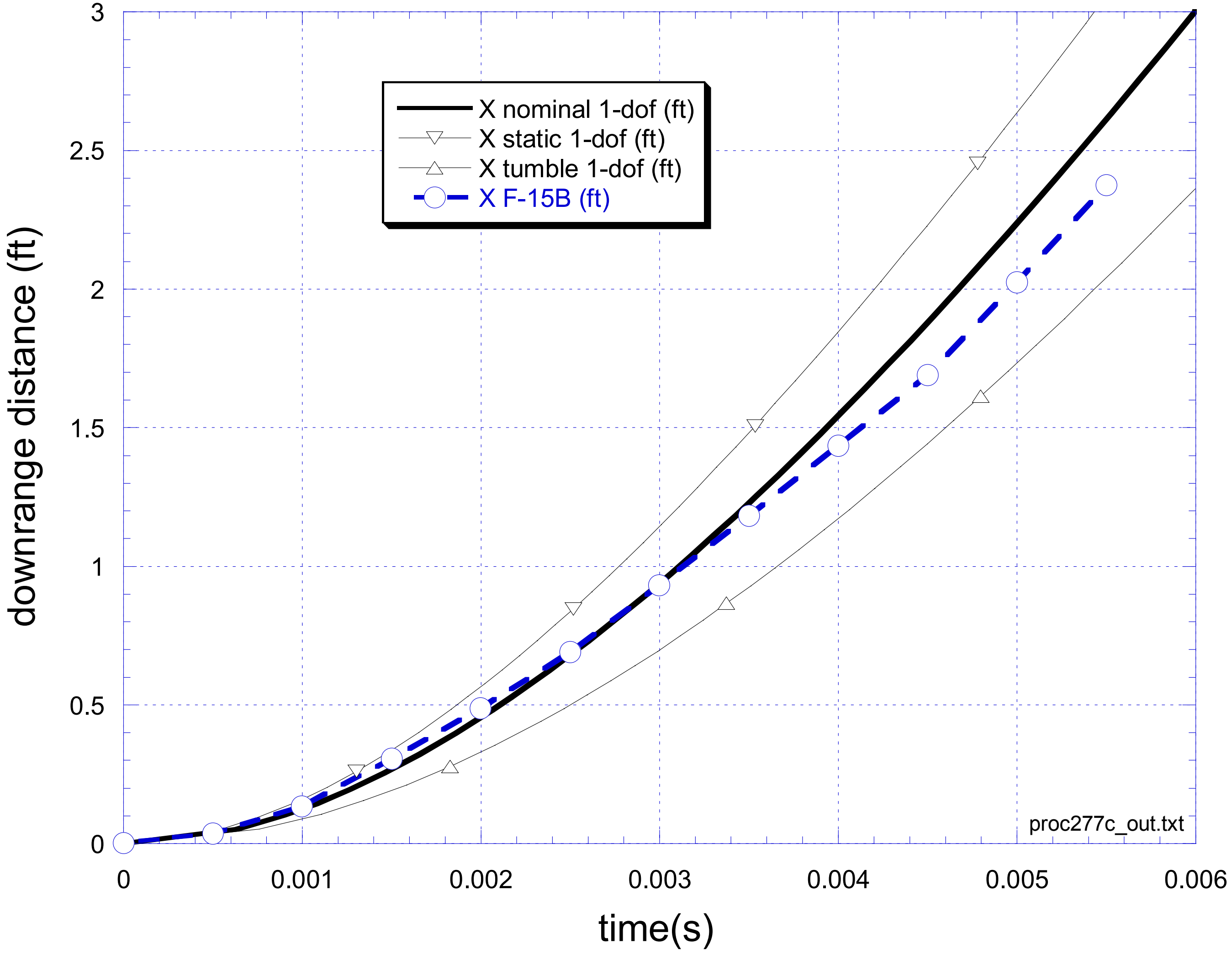
DFRC F-15B


836
NASA
Forward View
Aft View
BX-265 foam sheets
Flight Test Fixture

Results from F-15B Testing

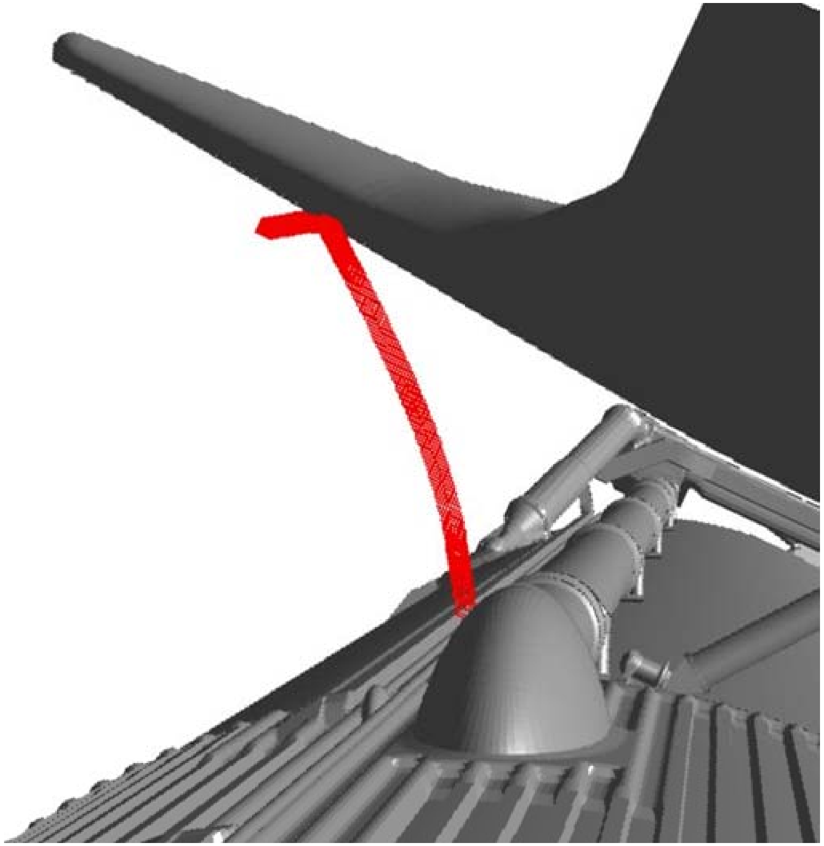
- Conducted 9 flights using BX-265 foam sheets
  - Total of 38 divots liberated
- All 31 of the supersonic divots ‘trimmed’
  - Of these, 30 of 31 rotated leading edge away from the sheet trimming with the small diameter facing forward
    - Divot C at Mach 1.6 and 850 psf passed through this first trim point and trimmed with the large diameter forward (only divot to behave in this fashion)
  - 2 of the 5 subsonic divots tumbled after one oscillation
- 36 divots survived the aerodynamic deceleration associated with being ejected into the flow field
  - Two of the three divots generated using the lowest successful ejection pressure rotated back into the sheet
    - As a result of re-contact with the sheet, the divots fractured into several pieces
  - Ejection pressure did not appear to affect divot geometry
    - All divots tended to be slightly smaller than predicted (using 30° angle assumption)

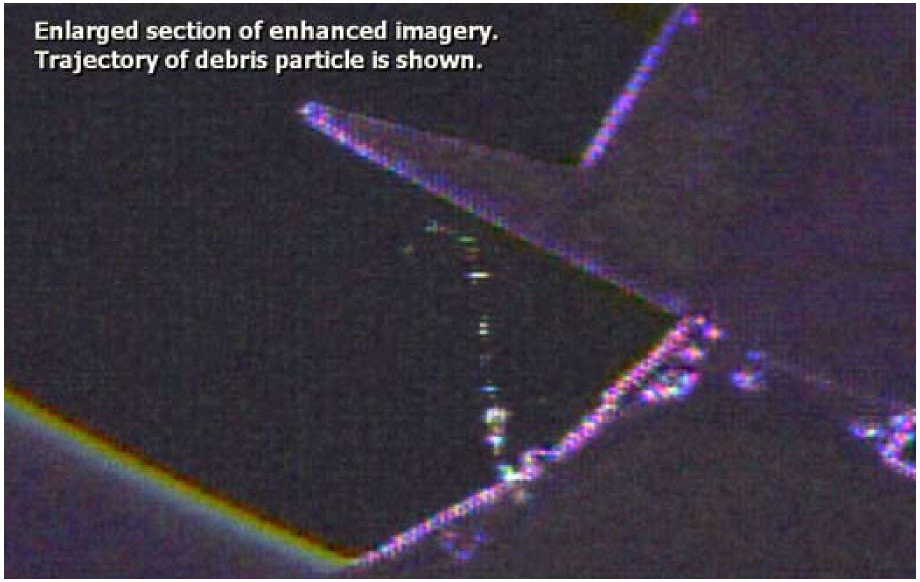
1-dof Comparison to F-15B Data



STS-114 Ice/Frost Ramp Debris Event

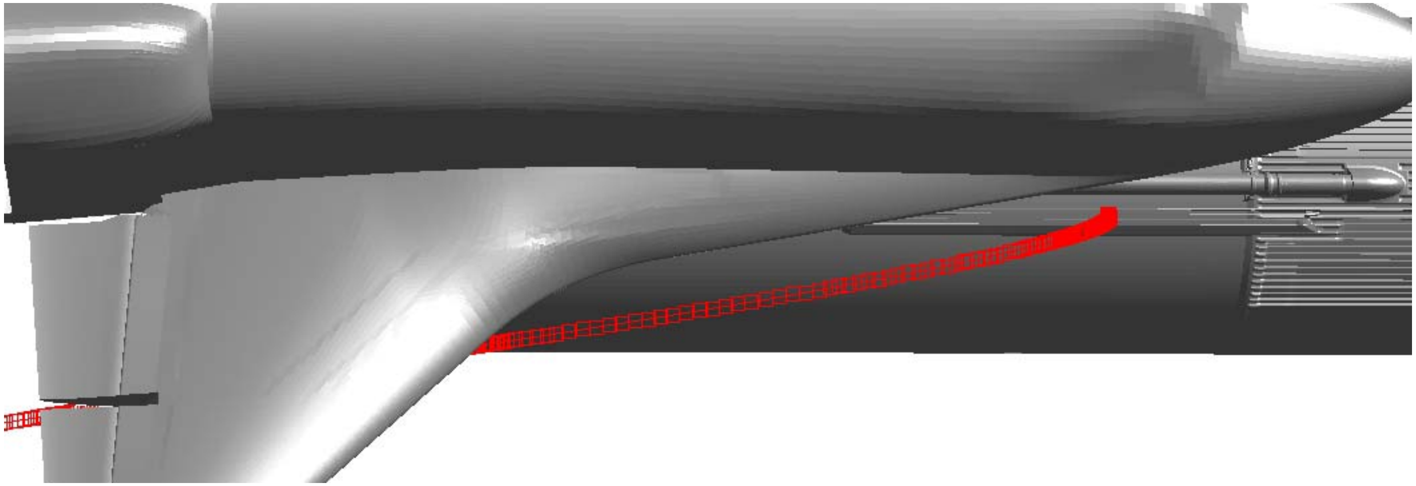
Computed and Enhanced Video Trajectories

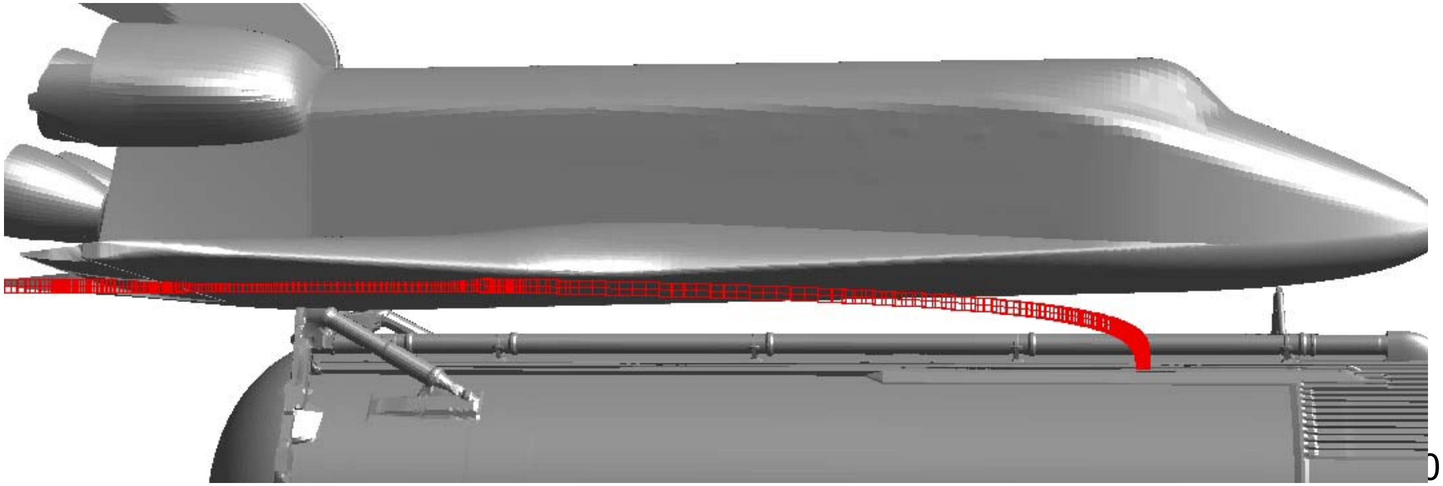




Mass = 0.03 lbm, 30 ft/sec pop-off velocity

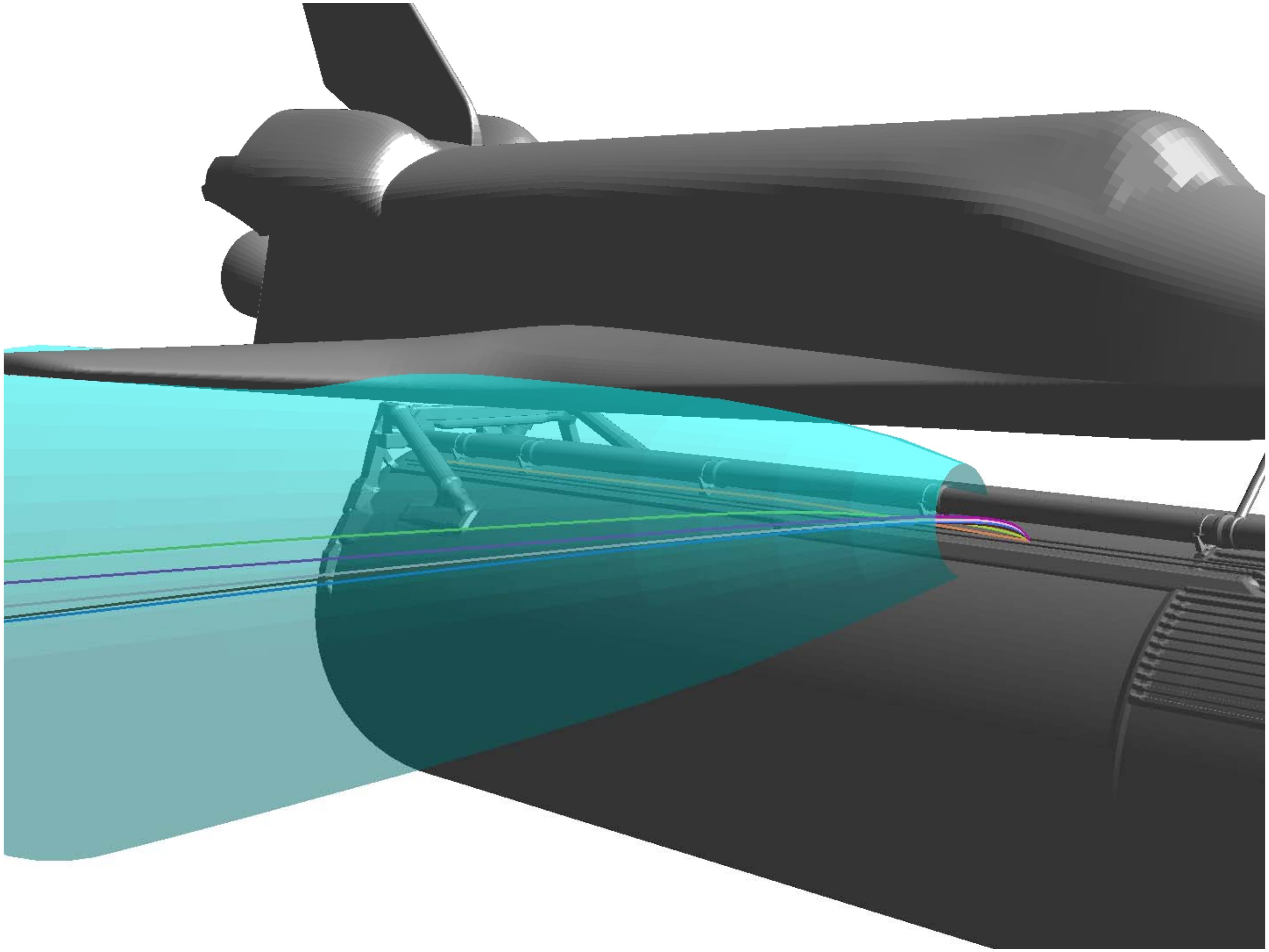
Trajectory, 0.03 lbm
30 ft/sec pop-off velocity





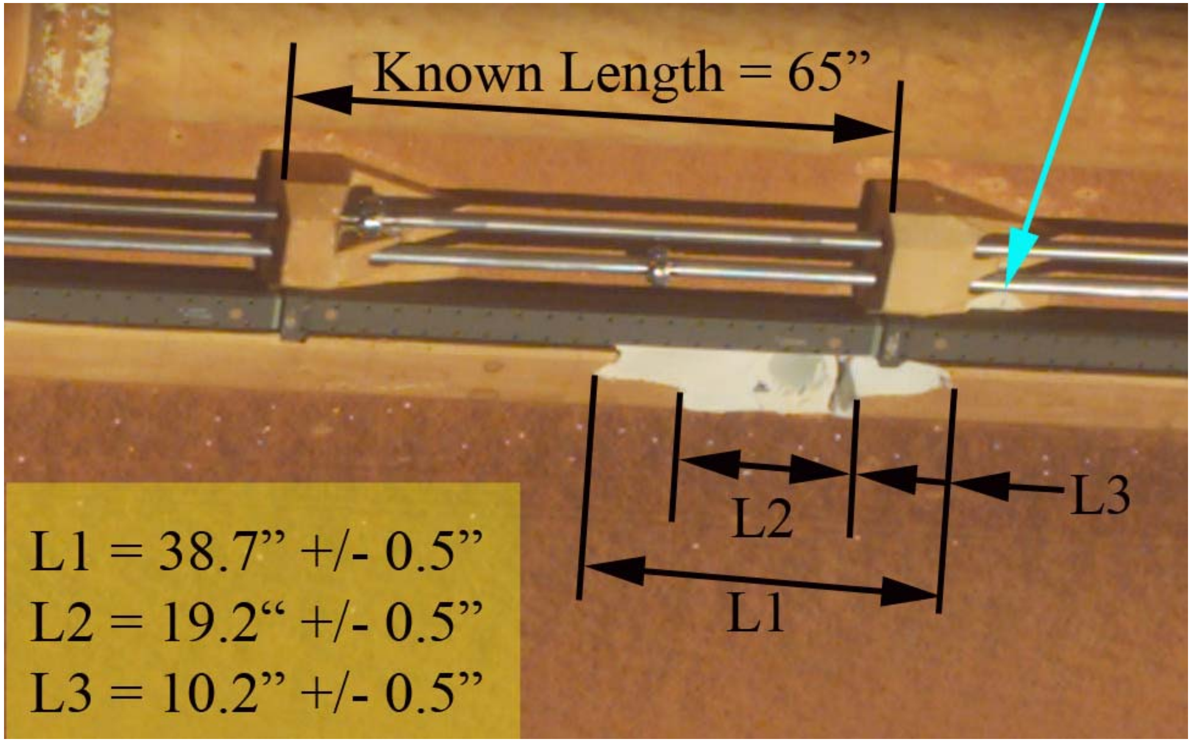
Mass=0.03 lbm Trajectories

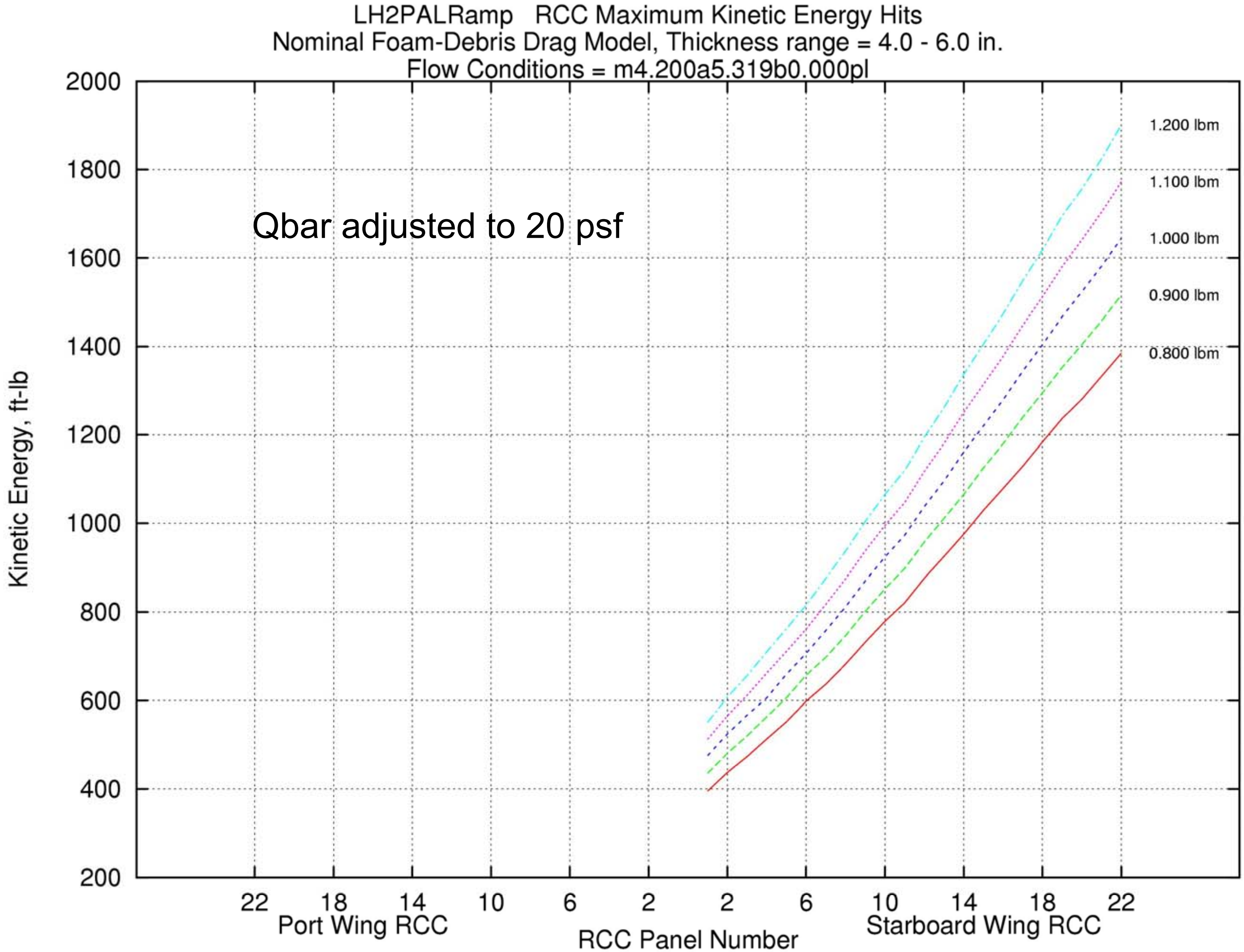
0 – 10 ft/sec pop-off velocity



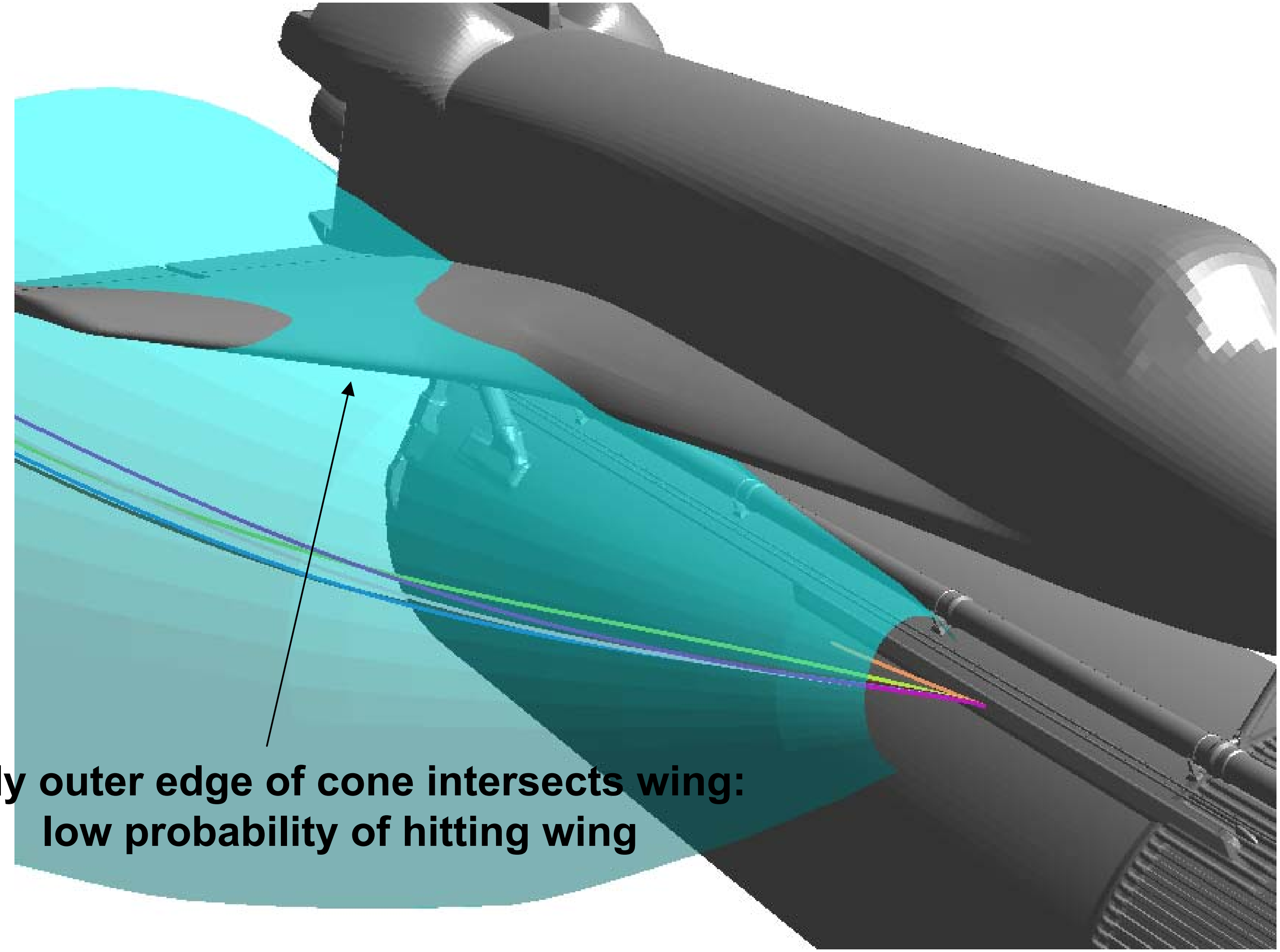
LH2 PAL Ramp Foam Debris

- LH2 PAL ramp release conditions at SRB Sep +5 sec
  - Mach=4.19, Qbar=19.5, α = 1.23 deg, β = -0.87 deg
- Mass estimated ~= 0.98 lbm
- BX-265 Foam density = 2.34 pcf




LH2PALRamp RCC Maximum Kinetic Energy Hits
Nominal Foam-Debris Drag Model, Thickness range = 4.0 - 6.0 in.
Flow Conditions = m4.200a5.319b0.000pl
Qbar adjusted to 20 psf
Kinetic Energy, ft-lb
2000
1800
1600
1400
1200
1000
800
600
400
200
1.200 lbm
1.100 lbm
1.000 lbm
0.900 lbm
0.800 lbm
22
18
14
10
6
2
2
6
10
14
18
22
Port Wing RCC
RCC Panel Number
Starboard Wing RCC

Mass=1.0 lbm Trajectories



Only outer edge of cone intersects wing: low probability of hitting wing

Concluding Remarks

- CFD simulations of SSLV ascent have become a value data tool for the program
  - Significant computational and experimental validation efforts
- Deterministic debris transport simulation has been used to quantify the debris environment during ascent
  - Being extended to reentry cases
- Probabilistic debris simulation capability under development, significantly aided by CFD simulations